Failure Contributors of MV Electrical Equipment and Condition Assessment Program Development

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Abstract: Implementation of condition assessment, or condition-based-maintenance, involves many disciplines such as failure analysis, on-line diagnostics, diagnostic data interpretation, management and communication, follow-up corrective actions and lastly the program maintenance. One of the difficult areas in the development of a comprehensive condition assessment program is the analysis of the probable contributing causes of failures, and selection of the appropriate on-line diagnostic tools to address the correct failure contributors. The specific failure contributors of the electrical power transmission and distribution equipment are documented in various sources, such as IEEE. This paper will illustrate the process of development of a comprehensive condition assessment program for medium voltage switchgear using the statistical data pertaining to the equipment failure contributing causes. Particular attention will be given to the selection of specific on-line diagnostic techniques that are available today and that will address the specific failure contributors. Presented only briefly will be the outage costs and RCM (Reliability Centered Maintenance) concepts, related to a condition assessment program.

Condition Assessment

Both condition assessment and condition-based-maintenance are concepts involving the application of new technologies and techniques of equipment diagnostics while the equipment remains in full operation. While some terminology may imply relatively new techniques, it should be born in mind that the idea of condition-based maintenance has been around for many years. As an example, a thermal replica, used in many temperature monitoring and protective devices, addresses one of the most important contributors of the electrical insulation aging, temperature.

The benefits of the condition-based maintenance programs lie in elimination of many time-based maintenance tasks, in exchange for maintenance tasks deemed necessary due to the actual condition of the equipment. While the specific condition is always monitored during normal operation, its evaluation serves to better manage the life and therefore the reliability of a specific asset. The corrective actions may take various forms such as through changes to the equipment-operating regime or specific discrete corrective actions to be conveniently scheduled for future planned outages [1].

The condition-based approach constitutes a dramatic qualitative leap in managing the equipment reliability compared to the conventional off-line diagnostics, where the condition of the equipment often remains unknown until an outage is underway. It follows that the condition-based maintenance approach offers reduction in the equipment downtime, improvement in the equipment reliability and dramatic reduction of the asset operating costs. Another advantage is the deferral of planned maintenance hence an increase in production equipment availability.

Failure Contributing Causes

IEEE Standard 493-1997, <u>IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems</u> documents the equipment failure data obtained through end-user surveys. This standard comprises of detailed data related to the reliability of various components of the electrical systems. The document appendixes contain the listing of specific causes that were identified as contributing to the failure of the equipment. For example, Appendix E contains such data for the switchgear bus and Appendix K for the circuit breakers.

A switchgear bus and circuit breakers are the two main components of the medium voltage switchgear, therefore by combining data from the two categories one can derive a composite distribution of failure contributing causes, ranked by their relative importance. While the IEEE standard did not aim at identification of specific initiating causes of the failures, it is possible to do so using intuitive approach, based on experience with medium voltage switchgear systems. Such step is necessary for selection of the appropriate on-line diagnostic technologies that could provide a predictive indicator for each specific initiating cause.

On-Line Diagnostic Technologies

Once the initiating cause of the failure modes has been identified and the appropriate on-line diagnostic technologies assigned, each on-line diagnostic practice can be ranked by its importance. The diagnostic technologies available today will be briefly discussed with the emphasis on their predictive indicators [3].

The following assumptions have been made concerning the appropriate on-line diagnostic technologies available today:

a) Diagnostics can be safely performed while the equipment is in full operation.

b) Diagnostics can be obtained periodically or via continuous monitoring of the specific condition.

c) Predictive indicators are clearly identifiable.

Failure Contributing Causes

Table 1 lists the failure contributing causes that relate to the switchgear bus category [2], for both the insulated bus and the bare bus.

Switchgear Bus Failure Contributing Causes (%)		
From IEEE Std 493-1997 Appendix E - Table XVIII	**Ins. Bus**	**Bare Bus**
Thermocycling	6.6	-
Mechanical Structure Failure	3.0	8.0
Mechanical Damage From Foreign Source	6.6	-
Shorting by Tools or Metal Objects	-	15.0
Shorting by Snakes, Birds, Rodents, etc.	3.0	-
Malfunction of Protective Relays	10.0	4.0
Improper Setting of Protective Device	-	4.0
Above Normal Ambient Temperature	3.0	-
Exposure to Chemical or Solvents	3.0	15.0
Exposure to Moisture	30.0	15.0
Exposure to Dust or Other Contaminants	10.0	19.0
Exposure to Non-Electrical Fire or Burning	6.6	-
Obstruction of Ventilation	-	8.0
Normal Deterioration from Age	10.0	4.0
Severe Weather Condition	3.0	4.0
Testing Error	-	4.0
Total	94.8	100.0

Table 1

Table 2 lists the failure contributing causes related to circuit breaker category [2] of two voltage levels. In the last column, the rates are combined for both voltage classes and normalized to a new 100 % base.

Circuit Breaker Failure Contributing Causes (%)			
From IEEE Std 493-1997 Appendix K, Table # 6	**601V to 15kV**	**34.5kV to 138kV**	**Norm.**
Overload - Persistent	25.0	-	12.5
Normal Deterioration from Age	-	22.0	11.0
Lubricant Loss, or Deficiency	25.0	11.0	18.0
Lack of Preventive Maintenance	25.0	11.0	18.0
Other	25.0	56.0	40.5
Total	100.0	100.0	100.0

Table 2

It is interesting to note that the two leading contributors were the exposure to moisture of 30 % in the insulated bus category (Table 1), and the exposure to dust and other contaminants of 19 % in the bare bus category, respectively. For MV circuit breakers (Table 2), such leading contributor is “other”, followed by the lubricant loss or lack of preventive maintenance. Tables 1 and 2 are combined into Table 3 to show an overall ranking of the failure contributing causes. The numbers for the insulated bus, bare bus and circuit breakers were combined and results normalized to the new 100 % base.

The most probable top three failure contributing causes for medium voltage switchgear are:

a) Exposure to moisture (17.7 %).
b) Exposure to dust and other contaminants (11.4 %).
c) Normal deterioration from age (9.8 %).

Note that the “other” category of 40.5 %, related only to circuit breakers, is not included in the cumulative ranking. As a result, only 86.3 % of all possible failure contributing causes are being addressed.

The assumption that only 86.3% of all possible failure contributing causes are being addressed is considered conservative since it is often difficult to separate the causes related to the switchgear bus and enclosures from those that pertain to circuit breakers. For example, a report of a switchgear failure related to thermal cycling, obstruction of ventilation, above normal ambient temperature or mechanical structure failures may involve the rear primary disconnect assemblies of circuit breakers, which are solely part of the circuit breaker. Similarly, above normal temperature and associated deterioration of the spring tension and mechanical structure failures can result in the failure of a rear disconnect assembly of the circuit breaker, thus being reported as "Other" in the circuit breaker survey results. Therefore, it can be concluded that some of the contributing causes identified as "Other" in the Circuit Breaker Failure Contributing Causes (Table 2) may have been reported as part of the Switchgear Bus Failure Contributing Causes (Table 1) and vice versa.

Now that the contributing causes for medium voltage switchgear have been prioritized, a listing can be developed of the most probable initiating causes. Table 4 cross-references the two. Several instances exist where more than one probable failure initiating cause contributes to a specific failure contributing cause identified by IEEE. For example, thermal cycling can result from loose electrical connections, variations of load current or ambient temperature, operation of switchgear cubicle heaters, and other causes.

Exposure to chemicals, moisture or other contaminants, commonly leads to deterioration of the electrical insulation system.

The exposure itself does not directly cause the failure, but it sets up the insulation system deterioration that eventually can cause the failure.

Understanding of the mechanism of this deterioration process is extremely important. The presence of contaminants usually results in surface tracking, or aids the development of irreversible corona damage to the insulation system. Both surface tracking and corona can be detected by the partial discharge instrumentation, which will be further discussed.
The last step in this process is to assign the appropriate weighting to each of the most probable initiating cause identified. Ideally, each percentage value listed in Table 3 for each of the possible initiating causes could be further subdivided for all of the causes identified. This would require an extensive amount of data and analysis, since the various potential initiating causes can be interrelated.

For example, the 17.7% assigned to exposure to moisture could be split between the three most probable potential initiating causes:

a) Corona or Surface Tracking
b) Enclosure Openings
c) Cubicle Heater Circuit Failure

The failure of the cubicle heater circuit is known to result in the gradual moisture accumulation which, in turn, can lead to surface tracking, insulation surface carbonization and eventual failure. Accidental loss of enclosure integrity with the sufficient size of the opening, on the other hand, can result in a rapid moisture accumulation and the flashover leading to the equipment destruction without any warning signs.

While more complex, rigorous approach in the data analysis may be justified when statistical accuracy is critical, we have chosen more straightforward method for the purpose of the process illustration. In Table 4, the percentage listed with each initiating cause reflects the combined occurrence of the specific cause. The values are normalized to a new 100 % base.

Contributing Failure Causes of Switchgear Bus and C. B. combined (%)				
Contributing Cause	**Ins. Bus**	**Bare Bus**	**C. B.**	**Normalized**
Thermocycling	6.6	-	12.5	7.5
Mechanical Structure Failure	3.0	8.0	-	4.3
Mechanical Damage From Foreign Source	6.6	-	-	2.6
Shorting by Tools or Metal Objects	-	15.0	-	5.9
Shorting by Snakes, Birds, Rodents, etc.	3.0	-	-	1.2
Malfunction of Protective Relays	10.0	4.0	-	5.5
Improper Setting of Protective Device	-	4.0	-	1.6
Above Normal Ambient Temperature	3.0	-	-	1.2
Exposure to Chemical or Solvents	3.0	15.0	-	7.1
Exposure to Moisture	30.0	15.0	-	17.7
Exposure to Dust or Other Contaminants	10.0	19.0	-	11.4
Exposure to Non-Electrical Fire or Burning	6.6	-	-	2.6
Obstruction of Ventilation	-	8.0	-	3.1
Normal Deterioration from Age	10.0	4.0	11.0	9.8
Severe Weather Condition	3.0	4.0	-	2.8
Testing Error	-	4.0	-	1.6
Lubricant Loss, or Deficiency	-	-	18.0	7.1
Lack of Preventive Maintenance	-	-	18.0	7.1
Other - Breaker Related	-	-	40.5	-
Total	94.8	100.0	100.0	100.0

Table 3

For example, the initiating cause of “enclosure openings”, or enclosure integrity, was listed with six different failure contributing causes:

a) Mechanical damage from foreign source (2.6 %)

b) Shorting by tools or metal objects (5.9 %)

c) Shorting by snakes, birds, rodents, etc. (1.2 %)

d) Exposure to chemicals or solvents (7.1 %)

e) Exposure to moisture (17.7 %)

f) Exposure to non-electrical fire or burning (2.6 %).

The last item was included since it involves the area around the enclosure that would be addressed by a maintenance-type corrective action. The above causes related to enclosure openings, enclosure integrity or the area surrounding the switchgear enclosure combine to 37.1 % of occurrences.

As another example, corona or surface tracking, was identified for four failure contributing causes:

Failure Contributing Causes for Switchgear Bus and Circuit Breakers	Most Probable Initiating Cause of Failure (Contributor)	(%)
Thermocycling	Loose connections, load current, internal temperature, ambient, cubicle heaters, etc.	7.5
Mechanical Structure Failure	Fatigue, vibration, electrical loose components	4.3
Mechanical Damage From Foreign Source	Accidental action during maintenance / Enclosure Openings	2.6
Shorting by Tools or Metal Objects	Accidental action during maintenance / Enclosure Openings	5.9
Shorting by Snakes, Birds, Rodents, etc.	Enclosure Openings	1.2
Malfunction of Protective Relays	Excessive mechanical/thermal stresses during abnormal system operation	5.5
Improper Setting of Protective Device	Excessive mechanical/thermal stresses during abnormal system operation	1.6
Above Normal Ambient Temperature	Ambient Temperature	1.2
Exposure to Chemical or Solvents	Corona or Surface Tracking / Enclosure Openings	7.1
Exposure to Moisture	Corona or Surface Tracking / Enclosure Openings / Cubicle Heater Circuit Failure	17.7
Exposure to Dust or Other Contaminants	Corona or Surface Tracking	11.4
Exposure to Non-Electrical Fire or Burning	External activity	2.6
Obstruction of Ventilation	Clogged door or other filters	3.1
Normal Deterioration from Age	Normal deterioration: corona or surface tracking of the insulation; contacts, interrupters, springs, mechanisms.	9.8
Severe Weather Condition	External activity	2.8
Testing Error	External activity	1.6
Lubricant Loss, or Deficiency	Overheating of the equipment and lubrication, aged lubricants or loss-of lubricants	7.1
Lack of Preventive Maintenance	External activity	7.1

Table 4

a) Exposure to chemicals or solvents (7.1 %)

b) Exposure to moisture (17.7 %)

c) Exposure to dust or other contaminants (11.4 %)

d) Normal deterioration with age (9.8 %)

The causes related to corona or surface tracking combine to 46.0 % of occurrences. In the last step, the combined values are normalized to the new 100 % base.

The result is shown in Table 5 below. In this table, listed are the technologies, techniques or measures that have been developed to mitigate, prevent or predict the occurrence of specific failure contributing causes as they appear in IEEE Standard.

Table 6 shows the effectiveness of such technologies, techniques or measures in terms of their overall impact in addressing the failures of the electrical switchgear and circuit breakers.

Most Probable Initiating Cause of Failure (Contributor)	**Available Solutions to address Initiating Causes**	**(%)**
Loose connections, load current, internal temperature, ambient, cubicle heaters, etc.	Infrared Thermography for Hot Spots	7.5
Fatigue, vibration, electrical loose components	Infrared Thermography for Hot Spots	4.3
Accidental action during maintenance / Enclosure Openings	Maintenance Training, Quality Control & Visual Inspections	2.6
Accidental action during maintenance / Enclosure Openings	Maintenance Training, Quality Control & Visual Inspections	5.9
Enclosure Openings	Visual Inspections	1.2
Relay failure	Periodic Relay Testing	5.5
Improper relay settings	Periodic Power System Study	1.6
Ambient Temperature	Design	1.2
Corona or Surface Tracking / Enclosure Opening	Partial Discharge Detection & Visual Inspection	7.1
Corona or Surface Tracking / Enclosure Opening / Heater Circuit Failure	PD Detection, Inspection and Heater Ammeter	17.7
Corona or Surface Tracking	Partial Discharge Detection (External visual inspection can not address internal defects)	11.4
External activity	Inspection of External area	2.6
Clogged door or other filters	Infrared Thermography for Hot Spots	3.1
Normal deterioration: corona or surface tracking the insulation; contacts, interrupters, springs, mechanisms, etc.	Partial Discharge Detection and Infrared Thermography for Hot Spots	9.8
External activity	Design	2.8
External activity	Design, Maintenance Training, Quality Control & Preventive maintenance	1.6
Overheating of equipment and lubrication age or loss-of lubricants	Infrared Thermography for Hot Spots	7.1
External activity	Preventive maintenance	7.1

Table 5

Predictive Diagnostic Solutions For MV Switchgear and Apparatus			
Technologies/Techniques addressing Failure Initiating Causes	**Total % Incidence**	**% Causes Addressed**	**On-Line Predictive Diagnostic Monitoring Technologies**
Thermal Replica	32.1	15.6	*Continuous temperature monitoring, not replica, commercially available*
Infrared Thermography for Hot Spots	**24.7**	**12.0**	***Available for periodic monitoring***
Vibro-accoustics for Circuit Breakers	11.4	5.6	*Not* yet *commercially available*
Maintenance -Training, Quality Control, Visual Inspections	10.1	4.9	*Effective Preventive Solution*
Visual Inspections (Switchgear Enclosure and Surrounding Area)	37.1	18.1	*Effective Preventive Solution*
Periodic Relay Testing	5.5	2.7	*Effective Preventive Solution*
Periodic Power System Study	1.6	0.8	*Effective Preventive Solution*
Partial Discharge Detection	**46.0**	**22.4**	***Available for periodic monitoring***
Preventive maintenance	8.7	4.2	*Effective Preventive Solution*
Total	177.2	86.3	***Addressable by CBM …..* 34.4 %**

Table 6

The numbers are normalized to a new base of 86.3 % to reflect the size of the addressable sample as discussed previously. It follows from this analysis that two on-line predictive technologies in particular, can address a large number of the contributing causes. They are Partial Discharge and Infrared Thermography technologies. For the sake of further discussion, also some potentially viable technologies, not commercially available today, are listed, such as vibro-accoustics.

On-Line Predictive Diagnostic Technologies and Solutions

Table 6 shows that more than one third of the failure contributing causes identified by IEEE can be mitigated by the two methods, Partial Discharge and Infrared Thermography, addressing 22.4 % and 12.0 % of failure causes respectively. The application of on-line technologies has three distinct advantages over the traditional (off-line) diagnostic techniques:

a) Diagnostics is performed in true equipment operating condition (electrical stress, temperature, and vibration).

b) No outage is necessary.

c) Significant costs savings realized.

We will briefly discuss both technologies with the emphasis on the failure cause detection.

On-Line Partial Discharge Technology

Corona and surface tracking are the key root causes of solid insulation deterioration in the switchgear and apparatus. If left untreated, corona and surface tracking will lead to irreversible insulation damage by creating a conductive path between the live conductors and ground, therefore resulting in a "fault". Such fault, or a full discharge, can be correlated to placing a thin bell wire between the live conductor and ground. The bell wire would immediately evaporate, resulting in an arc drawn between the live conductor and ground. At the medium voltage level the arc is often sustained until the voltage is removed. The air is a good insulator at room temperatures but as the temperature of air is increased to the temperature of an arc, it becomes a good conductor. This process is called the ionization of air, whereby the air molecules become electrical current carriers and plasma is formed. The current continues to flow until an upstream protective device interrupts the fault.

Partial discharges, on the other hand, are small arcs that occur within or between insulation materials, usually across a gas-filled void in the electrical insulation. It has been found that voids of 1 mil size break down at approximately 360 Volts, with a void of 0.3 mils having a breakdown voltage of 240 Volts [4]. This phenomenon is similar to an arc being drawn through the air, except this process doesn't sustain itself as the voltage across the void is bridged similar to shorting of a capacitor. In medium voltage systems, the energy contained by such charged void is not sufficient to maintain plasma that accompanies the full discharge. Instead, arc continues to reignite and extinguish itself in a rather repetitive fashion. In medium voltage systems (4160 Volts and above), the potential of 300 Volts can be easily developed across an internal void in the insulation system, resulting in the internal arcing, or partial discharge activity.

It should be noted that in low voltage systems, the voltage across the insulation is not sufficient to develop the required 300-Volt potential across a small void, therefore we do not witness corona damage or surface tracking in low voltage systems.

Corona can often be “heard” as distinct cracking sound. Although occurring in air, this arcing also causes deterioration of the solid insulation, which breaks down into a white powdery residue on its surface. Another byproduct of corona is the smell of ozone, which is the result of the oxygen molecule decomposition. Corona can also be observed visually if the arcing is severe and the area is in complete darkness.

Lastly, corona arcing is also accompanied by emission of electromagnetic waves at radio frequencies from 100 kHz to 100 MHz. Such radiation can be detected on the outside if the arcing is severe, directly observable or not shielded by metal barriers. As the internal insulation of the medium voltage metal-clad or metal-enclosed switchgear is very effectively shielded by design, a task of reliable sensing of partial discharges and corona poses us with a significant challenge.

Even clean and dry insulation will exhibit corona damage, as is often a case with older switchgear designs. Many older designs feature flat cooper bus covered with an insulation sleeve. The insulation sleeve enters the switchgear cell through a surrounding insulating support barrier with inherent small air gaps between the copper and the sleeve and between the sleeve and the support barrier. Sufficient potential can be capacitively coupled across these multiple air gaps. For this reason, it is common to find corona damage on older switchgear designs, at the point where the internal bus passes between cubicles.

This very problem was detected by on-line partial discharge analysis. Figure 1 shows the level of partial discharge activity for each cubicle across the subject MV switchgear line-up. High PD levels at cubicles # 8 and # 9 supported the recommendation for an internal inspection during a scheduled outage. Inspection revealed severe insulation deterioration at the bus transition sections between cubicles # 8 and # 9 (Figure 2). The damage was at the line-side of the feeder circuit breakers where the bus is totally enclosed by metal barriers. This section is neither visible nor accessible by the front or rear hinged doors. For the above reason, this type of deterioration is not normally detectable by hand-held ultra-sonic detectors due to the single and multiple metal barriers. Hand-held ultra-sonic detectors can

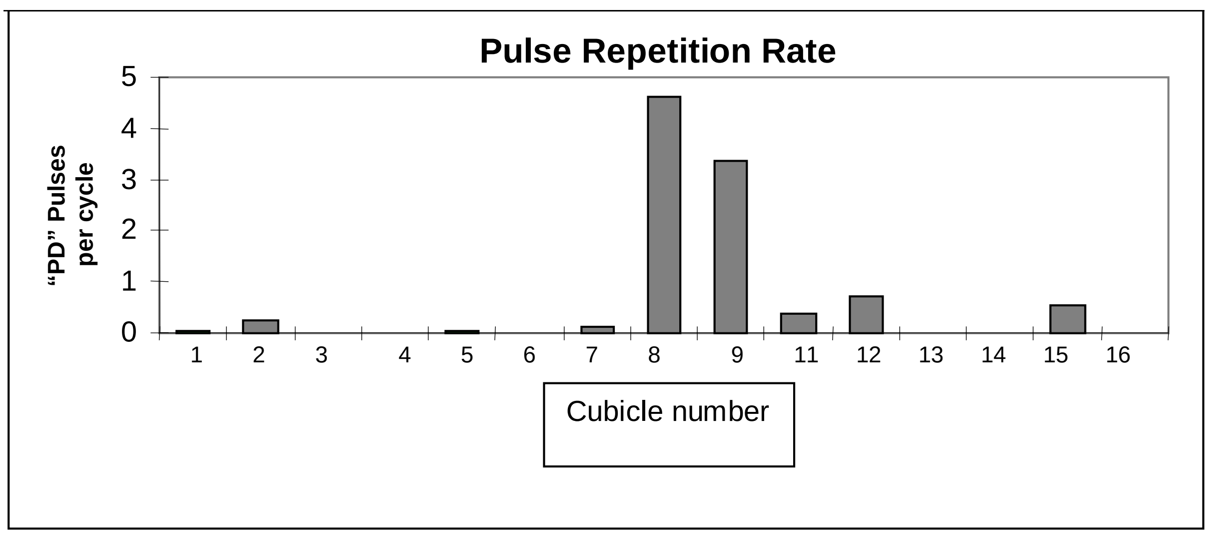

Figure 1
On-Line Partial Discharge Detection in medium voltage switchgear

help to pinpoint the specific source of PD within a switchgear cell, during an off-line AC High Potential test. This can be completed during the next scheduled outage, should on-line PD measurements indicate a potential problem.

Through the use of specially designed partial discharge sensors, the partial discharge activity can be detected behind the metal barrier assemblies, therefore allowing for on-line diagnostics of insulation deterioration associated with corona damage.

Figure 2
Corona detected and damage found between cubicles # 8-9

Surface tracking can start as corona, at high electrical stress points, but a contaminated insulation surface must exist for the surface tracking to progress. With a combination of contaminants and moisture on the insulation surface, a surface leakage current can flow. The associated heat losses can help evaporation of water and reduction of the contamination to thin

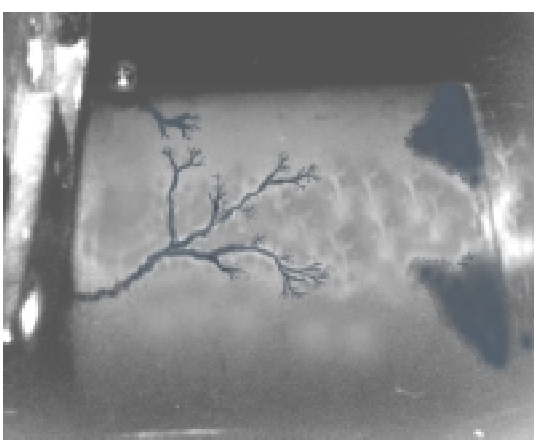

Figure 3
Surface Tracking on a 4160-Volt Circuit Breaker Bushing

semi-conductive coating, thereby formation of small arcs. These small arcs continue to burn at the insulation surface producing permanent carbon traces. Carbon is a conductor and its formation of the insulation surface aid in propagation of the “needle points” along the surface. This process of surface tracking and tree propagation (treeing) is irreversible. An example of surface tracking is shown in Figure 3.

This 4160-Volt bushing from an air circuit breaker has only about 5/8” of its surface intact. Inspection determined that the root cause of this damage was the surface tracking due to a gradual build-up of moisture in the cell due to the faulty cell heater for extended amount of time.

Corona damage and surface tracking are two primary root causes of insulation deterioration in medium voltage electrical systems. An on-line method for reliable detection of internal partial discharges was developed and experimentally verified for the voltage classes from 5 kV to 38 kV.

As shown earlier, a few on-line diagnostic techniques can address a significant number of failure causes in medium voltage switchgear and apparatus. To further economic return from implementation of any of the discussed techniques, also more conventional methods can be employed. For example, periodic surveys addressing partial discharges can be suitably combined with inspections addressing the integrity of the enclosures and surrounding areas, thereby addressing an additional 18% of the failure contributing causes at virtually no additional costs.

Infrared Thermography

Thermographic inspections of electrical switchgear have been an extremely valuable predictive diagnostic tool for many years. The thermographic instrumentation detects the infrared radiation, which is emitted by the surface of equipment under observation. A thermal image is constructed of the equipment under test, much like the video camera processes the visual image. Different colors represent different surface temperatures. Corrections often need to be applied to adjust for different reflectivity of the surfaces and other factors.

Hot spots from loose or deteriorated bus joints, or excessive heat from overheating contacts can be quickly identified. When different readings from phase conductors are obtained, individual phase loading needs to be taken into account. Various techniques are used to help the operator reliably pinpoint the source of heat and its probable cause, leading to reliable identification of appropriate corrective actions. With the help of a computer, thermographic images or video scans can be conveniently stored for documentation purposes.

Thermography requires the direct line-of-sight between the camera (gun) and the equipment to be inspected. The medium voltage switchgear needs to have hinged front and rear doors. Extra caution and maximum safety must be always exercised when opening enclosures of live equipment. While safety implications are obvious, care must be taken to minimize the possibility of an accidental trip from protective relays or interlocks. Extra care should also be taken around the switchgear equipped with flashover protection that uses light sensors to trigger the back-up protection. If the rear-hinged doors are opened, extreme caution must be exercised, as the bus may run very close to the doors or covers. The integrity of the hinges must be verified to ensure that the hinged door will not dislodge or otherwise come in contact with the live bus during opening.

NOTE: It is not recommended to attempt an inspection of live electrical equipment, without proper training and observing all safety precautions.

Other options are infrared view-through sites that are designed to allow for the passage of infrared radiation, whereas maintaining a safety barrier between the camera operator and the live components. These are usually small in diameter matching the infrared camera lens.
Thermographic inspections are very effective in identifying deterioration related to:

a) Thermal cycling, resulting in formation of hot spots.

b) Mechanical failures from loose connections.

c) Overheating from obstruction of ventilation.

d) Normal deterioration with age resulting in loose connections.

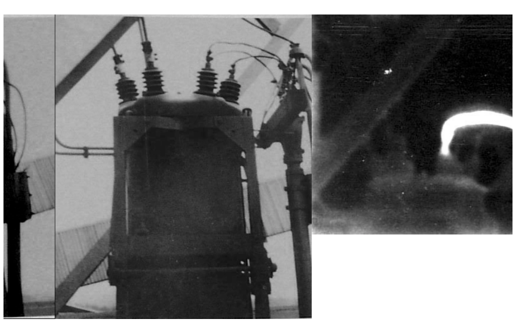

Figure 4
Infrared scan identifying overheated bushing connection on an outdoor Oil Circuit Breaker

Care must be exercised to complete the thermographic inspection in a safe manner, usually with two personnel present. Figure 4 shows an outdoor oil circuit breaker, with the close-up picture of "hot spot" in one of the bushing connections at the right-hand side of the circuit breaker.

Failure Related Costs

When implementing effective condition-base maintenance programs, the costs of such program and its benefits have to be scrutinized in detail. The IEEE Standard 493-1997 documents equipment failure rates in per unit-year notation for both switchgear bus and circuit breakers. Unit-years are defined as the number of switchgear cubicles or switches, in a plant, multiplied by the number of years of operation of the switchgear between expected failures.

For switchgear bus, the expected failure rate is 0.015 per unit-years with an average downtime of 29 hours per failure (Appendix K - Table I, page 388 – 601V-15kV and 34.5-138kV categories combined) [2]. For circuit breakers, the expected failure rate is 0.001 per unit-years, with an average downtime of 28 hours per failure (Appendix E - Table I, page 309) [2]. The combined failure rate for both switchgear bus and circuit breakers is 0.016 failures per unit-years, with an average downtime of 28.5 hours per failure.

Table 7 shows the data extrapolation for plants with 25, 50, 75 and 100 MV circuit breakers (cubicles or cells); for five years between failure events.

The effect of extending the time interval between failures is a potentially longer outage required to return the equipment back to operation.

For example, a plant with twenty-five MV cubicles may experience a single circuit breaker or cell failure every year. According to the IEEE data, 11.4 hours of downtime would be required on average to return the equipment to full functionality. One can speculate that the outage will be shorter if the failure is only related to the circuit breaker itself and a spare device is available. On the other hand, if the cubicle has been damaged by fire, significantly longer outage will be required to clean up the switchgear cubicle before installing the spare circuit breaker.

A five-year event, with associated 57-hour outage, can be thought of as a failure of the main bus of the switchgear lineup or a failure occurring at multiple locations in a distribution system. Such serious failure will require the following:

a) De-energization of the entire switchgear line-up.
b) Removal of all damaged bus and insulation.
c) Repair or replacement of components often requiring custom bus fitting.
d) Inspection and cleaning of all associated equipment, testing and startup.

Such a 57-hour long outage translates to approximately 2.5 days of round-the-clock emergency repair. In the case of entire line-up failure, 2.5 days is a reasonable estimate to perform all of the above work.

In another example we will assume that a plant had fifty MV circuit breaker cells, and had not experienced a cubicle or a circuit breaker failure in three years. The expected hours of downtime for the probable failure in year # 3 would be: *(0.016 failures/unit-years)* times *(50 breaker units)* times *(3 Years)* times *(28.5 hours per failure)*, or 68.4 hours of expected downtime due to a failure associated with the medium voltage switchgear bus or circuit breakers. This equals to three days of round-the-clock emergency repair, but it may involve multiple failures; hence 1.5 days of round-the-clock emergency repair for two separate failures.

Table 7 shows the worst case of a 228-hour outage for a plant with one hundred of MV cubicles and no failure in five years. Such event equals to one major outage of complete switchgear (line-side bus) for 9.5 days, or five separate failures (load-side bus or circuit breakers) averaging 2 days.

Although the above examples are based on the official IEEE survey data [2], actual experience may suggest somewhat lower numbers. This may come from the fact that the survey may tend to favor most of the serious incidents while the small, local failures may have been unreported. Those of us who experienced such major switchgear failures are well aware of the extensive work involved, and the length of associated downtime.

As an example, a plant may operate for many years without a major bus or circuit breaker failure, putting such extrapolations in question, especially for recently erected installations. The above IEEE derived data is the composite of responses from many facilities with varied operating and environmental conditions, as well as varied maintenance practices. The adaptation of this data attempts to provide a relative costs for such failures, which will vary from plant to plant.

To translate the outage data into actual costs the following factors must be considered:

a) Lost Sales
b) Lost production margin
c) Downturn and start-up costs
d) Product waste costs
e) Repair or replacement costs
f) Environmental cleanup costs

Probable Hours of Downtime	**# of MV Breakers in the Plant**			
Years between Failure Events	**25**	**50**	**75**	**100**
One (1)	11.4	22.8	34.2	45.6
Three (3)	34.2	68.4	102.6	136.8
Five (5)	57.0	114.0	171.0	228.0

Table 7

When expressed in per-unit notation the costs need to be multiplied by the “Hours of Outage” from Table 7 above.

Reliability Centered Maintenance (RCM)

Reliability Centered Maintenance involves the evaluation of complete systems and sub-systems for the proper allocation of resources [1]. This study is performed by outside consultants or in-house personnel after proper RCM training.

In the area of electrical switchgear assemblies, there is a basis to perform an RCM review on each switchgear assembly, or substation, as a single-unit. In other words, the criticality of all system busses needs to be evaluated on the basis of the loads supplied and the effects on safety, environment and production. This type of analysis should first be completed by evaluating each switchgear assembly as a complete unit, since a failure in one switchgear bus, or one circuit breaker can result in the entire line-up being de-energized. Following this evaluation, each circuit breaker can then be evaluated with the appropriate review of the individual loads supplied.

The results can aid in the appropriation of resources from one switchgear assembly to another, or one substation to another.

Summary

This paper has presented a concept of development of a Condition Assessment Program for medium voltage switchgear and circuit breakers. The program development started with an analysis of the equipment failure contributing causes and the survey data documented by IEEE. Using experience and intuitive approach, the data was analyzed and the most probable initiating causes of each failure mode were assigned to each contributing cause.

The available on-line monitoring diagnostic technologies were reviewed and selected to address the failure initiating causes in the order of their importance. It was concluded that approximately 50% of the contributing failure causes identified by IEEE could be addressed by the commercially available technologies and techniques.

The two on-line diagnostic technologies were identified:

a) Partial Discharge Diagnostics, addressing approximately 22.4% of the failures, and

b) Infrared Thermography with the potential of addressing approximately 12.0% of the failures.

Most products in this category are still based on periodic (discreet) rather than continuous monitoring. However, significant achievements have recently been accomplished in development of the partial discharge continuous monitoring systems. It is the authors' strong belief that especially the latter technologies will form the basis for implementation of the economically viable condition-based monitoring programs for the medium voltage switchgear in the near future. The first application of these concepts will undoubtedly be in the processes of higher criticality, such as in the distribution systems in the paper mills, electronic manufacturing, power plants, refineries and other industries.

It was also demonstrated that the application of the condition-based maintenance can be conveniently combined with more conventional maintenance approaches. For example, the additional 18 % of contributing failure causes, related to enclosure and surrounding areas, can be cost effectively addressed by inspection either during the partial discharge or thermographic surveys.

Finally, safety related issues were shown as having probable effect on approximately 5 % of the contributing failure causes for MV switchgear. Regardless of the probabilistic results, safety issues should always be given the highest priority.

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