Electrical Equipment Condition Assessment Using On-Line Solid Insulation Sampling

Importance of Electrical Insulation

Electrical insulation plays a vital role in the design and operation of all electrical equipment and systems. The insulation’s primary function is to isolate energized components of different potentials from each other and ground. Various defects, contamination, and aging mechanisms cause insulation deterioration that leads to complete failure or insulation breakdown. In medium- and high-voltage equipment, complete insulation failure is preceded by partial discharge (PD) or partial failure of the insulation. Figure 1, which is derived from Table 36 of the IEEE Gold Book on Electrical Reliability, clearly illustrates the high percentage of electrical equipment failures caused by insulation breakdown. It reasons that by avoiding insulation breakdown, electrical equipment failure can be reduced dramatically, and the corresponding overall electrical system reliability will be increased tremendously. This goal is accomplished by first detecting partial discharge activity in electrical equipment and then by taking proactive maintenance, repair, or replacement actions.

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage of Insulation Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformers</td>
<td>84%</td>
</tr>
<tr>
<td>Circuit Breakers</td>
<td>21%</td>
</tr>
<tr>
<td>Disconnect Switches</td>
<td>15%</td>
</tr>
<tr>
<td>Insulated Switchgear Bus</td>
<td>95%</td>
</tr>
<tr>
<td>Bus Duct</td>
<td>90%</td>
</tr>
<tr>
<td>Cable</td>
<td>89%</td>
</tr>
<tr>
<td>Cable Joints (splices)</td>
<td>91%</td>
</tr>
<tr>
<td>Cable Terminations</td>
<td>87%</td>
</tr>
</tbody>
</table>

Figure 1 – Total Failures Due to Insulation Breakdown
Insulation Sampling and Evaluation Technologies

There are three types of insulation: solid, liquid and gas.

The most widely used type of liquid dielectric is mineral oil. Mineral oil is used in transformers primarily for insulating and cooling purposes. Electrical transformers contain over 4.5 billion gallons of fluid in the United States alone. Circuit breakers, load tap-changers and distribution oil fuse cutouts utilize mineral oil for insulating, cooling (heat transfer), and arc-quenching purposes.

In-service transformer oil sampling and analysis has been used for many decades to provide valuable information regarding both the condition of the dielectric and the electrical condition of the transformer itself. Because of the low cost of the analysis and the ease in which samples can be taken, oil sampling has become the most frequent test performed on transformers today. In fact, many preventive maintenance programs include annual transformer fluid analysis requirements.

In recent years, a great deal of advancement has been made in the analysis of dielectric fluids contained in load tap-changers and oil circuit breakers. Like transformers, the analysis reveals both the condition of the dielectric and the equipment itself, such as abnormal contact wear. Sampling of these devices is being adopted into more and more maintenance programs today.

Except for air, or the lack of it (vacuum), sulfur-hexafluoride (SF₆) is the most widely used gas dielectric in the electrical industry. SF₆ is used primarily in high-voltage circuit breakers and gas insulated switchgear for its good insulating and arc-quenching capabilities. Recent advancements in the analysis of SF₆ gas samples have led to the growing use of this technology for the assessment of dielectric and circuit breaker condition.

Solid insulation is by far the most widely used dielectric in the electrical industry. Switchgear, cables, dry-type transformers, and many other electrical devices employ numerous types of solid insulating materials. Even liquid- and gas-insulated equipment incorporate solid insulation components in their design. Unfortunately, no practical, non-intrusive insulation sampling and analysis method has existed for solid dielectrics. Until recently, this left traditional off-line (de-energized) dielectric testing as the only means available to evaluate solid insulation. These traditional field dielectric tests are limited to testing the bulk of the insulation and often these tests fall well short of expectations in regard to detecting localized solid dielectric defects, which lead to their eventual failure.

Partial Discharge Analysis

Partial Discharge testing of medium- and high-voltage equipment has been recognized for several decades (40-60 years) as a valuable means of assessing insulation condition in the laboratory environment for quality assurance purposes. Recent advancements in instrumentation hardware performance, sensor technologies, measurement techniques, data acquisition, and analysis software and digital filtering methods for noise reduction have led to the development of a new generation of PD test equipment for field use. This new PD equipment is capable of reliably assessing solid insulation condition while the associated equipment remains in service.

Chief advantages of performing on-line field partial discharge surveys are:

- It is a nonintrusive test, requiring no interruption of service and is performed under normal operating voltage.
- It is a predictive test, indicating specific symptoms in advance of the failure.
- It is a nondestructive test; it does not test to failure or adversely affect the equipment under test.
- It need not use any overvoltages, thereby not exposing the tested equipment to higher voltage stresses than those encountered under normal operating conditions.
- Trending can be accomplished by storing results to allow comparison with future tests.
- In many instances the site of the partial discharge occurrence can be located within the test object so the localized problem can be repaired.
- The cost to perform a partial discharge survey is relatively inexpensive, on the same order of magnitude as the cost of performing an infrared survey at most facilities.

Partial discharge testing in the field has been performed routinely overseas throughout Europe for many years, and its popularity is growing very quickly in the United States. This PD testing has proven to be a very valuable on-line prediction tool to reduce failures of medium- and high-voltage equipment.

Depending on the apparatus that is being evaluated, partial discharge can be detected using electromagnetic, acoustic emission or capacitive sensors to measure the resultant radio frequency signals created by the minute “sparking” that occurs due to partial failure of the insulation.
Not Infrared

Annual partial discharge surveys of medium- and high-voltage switchgear, cables, transformers, and other equipment is being applied in a similar manner as infrared surveys are used to detect current-related problems such as loose connections or overloading. Partial discharge testing differs as it detects insulation or voltage-related problems that cannot be found with infrared test equipment. Additionally, partial-discharge testing does not require a clear line of sight to the object being evaluated as does infrared. Therefore, partial discharges occurring inside of switchgear, transformers, or down lengths of cables can be detected and evaluated by recording the associated electrical field or radio frequency signals that they create.

Field Partial Discharge Testing Difficulties

There are two basic types of on-line solid insulation partial discharge testing equipment. One type is the well-known hand-held ultrasonic emission detector, which is used for detecting air-born partial discharge or corona in outdoor substations or inside switchgear. This device is useful and has led to the discovery of many electrical insulation problems. However, there are many disadvantages with this testing. The sensor requires a clear air path to the problem source and cannot look inside of equipment or cables. The test equipment cannot distinguish the difference between corona (discharge into air), which may be relatively harmless and partial discharge, which is very destructive. In electrical noisy environments such as high-voltage substations or mechanically noisy environments such as processing lines, this technology is often ineffective due to high background electrical or mechanical noise. Additionally, no true quantitative measurement of partial discharge activity can be made using ultrasonic emission testing only.

The other type of on-line solid insulation testing equipment utilizes sophisticated measurement devices to detect, record, and measure partial discharge. This type of equipment, shown in Figure 2, works extremely well to identify and quantify harmful partial-discharge activity. This equipment also detects partial discharge within the insulation and does not require a clear line of sight to the defect. This type of technology is now playing a key role in the condition assessment of electrical equipment employing solid insulation.

There are two historical disadvantages to this type of test equipment, and these disadvantages have prevented widespread field use of the equipment by service organizations and utilities in the US. The first problem is that the equipment is quite expensive ($75K - $125K). The second issue is that it requires extensive partial discharge analysis training and experience in order to interpret the signals and obtain meaningful results.

New Solutions

Technological advances have led to the development of new equipment and partial-discharge survey methods that greatly reduce the cost of the instrumentation and greatly simplify the field sampling and laboratory data analysis processes.

The new field partial-discharge sampling kit consists of three types of sensors which interconnect to digital processing hardware and signal conditioning devices that then save the partial-discharge signature to a built-in computer. Simplified procedures allow the field technician to easily sample and record the solid insulation signatures to a file on the PC. When the job is complete, the electronic files are sent via e-mail or Internet to the solid insulation laboratory where centralized expert analysis and evaluation is performed. The customer receives an electronic report as shown in Figures 3 and 4 for each item sampled. The new solid insulation sampling equipment is available to service organizations through an economically attractive lease program. This method of sampling and analyzing solid insulation is similar to the approach used to sample and analyze transformer oil as follows.

A. The sampling procedure is easy to learn.
B. The person performing the sampling need not possess a high level of specialized technical expertise.
C. The cost of the sampling equipment lease is low.
D. The information contained in the report provides an accurate indication of the insulation condition, the level of which can be more informative than oil test reports.

E. Sampling is performed on-line and therefore does not require an outage.

F. Sampling does not require contact with any live parts, so it is relatively safe.

G. The results can be trended to predict impending failures.

Solid PD sampling has the following additional advantages:

1. The sampling is very fast, about 1 minute per component.
2. The laboratory analysis cost is much less than that of an oil sample.
3. Electronic file transfers via e-mail can allow for immediate emergency analysis.
4. Continuous monitoring of critical equipment is possible via the Internet with optional equipment.
5. There is no environmental spill risk or need for sample disposal.
6. In addition to solid insulation, partial discharge sampling can be successfully performed on liquid and gas apparatus also.
7. The lease arrangement minimizes equipment investment and eliminates equipment obsolescence risks to the service provider.

Since oil and gas sampling are also very good technologies, PD sampling should not be used in lieu of these methods. PD sampling of apparatus using these types of insulation should be used to supplement the traditional tests. PD sampling also supplements traditional outage-based preventive maintenance. By performing the PD sampling before the scheduled outage, additional resources can be allocated to perform corrective actions.

**Conclusion**

The low cost, easy to use, electronic signature analysis program for solid insulation now allows convenient and cost effective sampling of medium and high voltage components to be performed by local service organizations or on-site maintenance personnel. Independent, third party experts, remote from the job-site, can inexpensively perform the difficult chore of identifying and evaluating the component’s insulation condition by using electronic data transfer through e-mail. Utilization of this new tool will allow a much greater
amount of equipment to be analyzed nonintrusively which will result in a much lower incidence of electrical failure and a greater increase in overall electrical reliability.

Don received his BSEE from Carnegie Mellon University. He is a NETA Certified Technician and a Certified Corona Technician. Don has nearly twenty-five years of practical field and laboratory electrical testing experience. He is presently the Vice President of Hampton Tedder Technical Services, and is a cofounder of I.Q. Services, which provides quality based and affordable solutions for the partial discharge field testing industry.

Figure 4 – Sample Partial Discharge Test Report, page 2

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