Trends in Power Transformer Failure Analysis

ABSTRACT

This article will introduce the reader to the importance of failure investigations, discuss the need for guidelines and the standards organisations work that is underway to provide the guidelines.

The concept of using the Scientific Method is introduced and existing processes are described.

Limitations of postmortem investigations are identified along with best practices for investigations.

INTRODUCTION

Failure investigations are becoming increasingly important in these days when assets like power transformers cost in the millions of euros or dollars and consolidation in the utility industry has resulted in the operators wanting the maximum capability from their assets.

Transformer failures have been investigated since the beginning of the electric utility industry. Each manufacturer can probably identify their own problem areas from factory failures, quality programme results and experience. However, the operators (utilities) may not possess sufficient quantities of a manufacturer or particular design to recognise the problem areas. Statistics such as those which, in the US and elsewhere, might result in a recall of an automobile model which may not exist in quantities sufficient to establish patterns of defects. Further, there is no regulatory body to require such a "recall." The owner/operator of the transformer is expected to be an informed consumer. The good news is that the power transformer is a highly engineered and tested product which has a significant life span. The informed consumer can make judgments about operation and maintenance knowing the root cause of failures on the system.

NEED FOR GUIDELINES

Failure reporting has taken place in the form of surveys published by organisations such as the International Council on Large Electric Systems (CIGRE WG A2.37 Transformer Reliability Survey), Edison Electric Institute (EEI Transmission and Distribution Committee), and the Institute of Electrical and Electronics Engineers – Industry Applications Society (IEEE/IAS). The EEI stopped publishing the results of their survey about the time that the utility deregulation movement got underway in the US. Some of the statistics reported by IEEE/IAS in the "Color Book Series" rely on data collected by the US Army Corp of Engineers in the 1970's. It is now left largely to the user to develop their own reliability statistics for transformers.

It was recognised long ago that the development of failure reporting guidelines was necessary. What was a defect to one user might be a major failure to another. This situation was observed in the data collected by EEI. This discrepancy led to the development of the *IEEE Guide for Reporting Failure Data for Power Transformers and Shunt Reactors on Electric Utility Power Systems*. Unfortunately, EEI no longer reported failure statistics a short time after publication of the Failure Reporting Guide. As the effort unfolded to develop failure statistics, it became clear that failure analysis guidelines were also necessary. The analysis guidelines, if effective, will result in four important things:

- Establish a common set of steps to investigate failures,
- Ideally, reach the same conclusion on root cause when presented with the same data,
- Result in sharing of performance between manufacturers and operators, and
- Produce meaningful statistics for transformer performance (failure rates, mean-time-to-failure, and so forth).

STANDARDS ORGANISATIONS WORK UNDERWAY

In CIGRE, there is a Working Group A2.4.5 on Transformer Failure Investigation and Postmortem Analysis which is underway. The Working Group scope states, *"This WG will develop a structured procedure from the decision to take the transformer and shunt reactor out of service to careful dismounting. The main following activities will be covered by this WG:*

- State of the art of postmortem analysis (IEEE C57.125-1991 and any other relevant existing documents)
- How to make an external and internal inspection of different components
- Important information to collect: diagnostics, protection, operation and maintenance records, etc.
- Availability and significance of design data, material used, etc.
- Documentation during the dismounting, check lists
- Additional checks, e. g. clamping pressure…
- Paper sampling: precautions, which winding, axial/radial position, correlation with temperature, number of samples, conservation and storage of the samples, parameters to be investigated (Task Force to be leaded by SC D1)
- Collection of pictures of postmortem analysis with examples of common failures and the associated failure investigation
- Best practices for failure report and scrapping report
- Economic aspect of postmortem analysis (cost, value, constraints, etc.)"

In the IEEE/PES Transformers Committee there is a Working Group on revision of *C57.125 Guide for Failure Investigation, Documentation, Analysis and Reporting for Power Transformers and Shunt Reactors* which has the task of revising and merging two existing documents. These IEEE Guides have been used since they were originally published in the 1980's and 1990's and reaffirmed as recently as 2005. The current revision will provide updates to technologies used in testing and evaluating transformer condition and include the work on reliability assessment contained in the previous guide. The Working


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Group is preparing a document whose scope "...recommends a procedure to be used to perform a failure analysis and the reporting and statistical analysis of reliability of power transformers and shunt reactors used on electric power systems." The Guide includes:

- Definitions
- Steps to Determination and Investigation of a Failure Occurrence
- Preparation Items
- Data Collection Checklists
- Analysis of common failure modes
- Failure Reporting guidelines (and guidance to develop a statistical database for reliability evaluation).

The Working Group has produced several drafts and expects to ballot in the next year.

SCIENTIFIC METHOD

Application of the Scientific Method is necessary when investigating a transformer failure or suspected failure. This requires analysis of the facts and data present, establishment of an hypothesis of failure, testing the hypothesis against the available data, collecting more data to confirm or refute the hypothesis, and reporting the results. Testing the hypothesis might include modeling or developing experiments to confirm the results (these experiments may take the form of comparison with other non-failed units of similar design, testing against established norms or comparison of test results on adjacent phases). After testing the hypothesis, it might be necessary to modify the hypothesis. This iterative process will come as close as possible to determining the root cause of the failure.

LIMITATIONS OF POSTMORTEM INVESTIGATIONS

Power transformer failure investigations must start with an understanding of the failure mechanisms possible and an understanding of the system in which the transformer is applied. Relevant (and some irrelevant) information leading up to and following the supposed failure must be available for analysis. This requires collection of fault recorder, sequence-of-events recorder, protective relay operation, protective device operation (fuses or circuit breakers), and alarm conditions prior to and subsequent to the outage, if one occurred. This data can include past alarm conditions that have been corrected, previous trip operations that have occurred, and system events which are similar to the current event.

If this type of data is not collected immediately after the suspected failure or if such data collection is not part of the practices of the utility, the failure event cannot be accurately reproduced. Likewise, if routine diagnostic testing is not part of the maintenance routine, comparison of test results with previous trends will be difficult or impossible. A well execut-

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ed maintenance programme is critical to investigations.

It must also be recognised that, in some cases, the damage done after a failure by the energy available on the power system can mask or destroy evidence of the root cause of the failure. This is one reason that routine monitoring of the transformer is important:

- to observe detrimental trends in performance of the insulating system which, if left uncorrected, could lead to failure resulting in an outage, and
- identify events which may have done damage to the transformer (such as damage resulting from through-faults, damage which is the result of improper or inadequate maintenance and repairs or damage from abnormal system conditions like over-voltages, abnormal frequency excursions, etc).

Of course, not all failures manifest themselves in an outage or protective device operation. Routine testing or on-line monitoring can detect abnormal conditions. These situations are sometimes confounding to the transformer operator – Are these results conclusive enough to remove the asset from service to attempt repairs and can repairs be successful? There are few transformer operators who "run-to-failure" with the additional risks that this practice entails. But when is the appropriate time to remove a transformer from service? Too soon and the system is operating in a higher risk mode or the cost of a replacement is necessary. Too late, and the result may be a catastrophic failure. Transformers which have a history of test results can be better evaluated than those that do not. Some transformers have operated for years with low levels of combustible gas being generated. Some have long history of higher than normal tan-delta (power factor). It is important to know when a test result is out of tolerance and unacceptable. Trending of results may be the best approach for the examples given but for other tests, the results can lead to "go" or "no-go" results. Experience is generally necessary to properly make this determination. The C57.125 guide points the reader to possible conclusions given various sets of test data or observed conditions. Final determination of root cause ultimately requires disassembly or dismounting of the transformer to investigate the internal conditions found following the failure.

Factors to take into account when making the decision to remove a transformer from service should include:

- risk of outage
- consequence of outage
- value of the transformer and surrounding equipment
- the ability of the system to operate without the transformer in-service.

BEST PRACTICES FOR INVESTIGATIONS

The rapid collection of data and observations from both the transformer and the system conditions at the time the decision is made to remove the transformer from service, either by human intervention or by automatic trip, is important to the successful analysis of transformer failures.

It is also important to operate and investigate in a safe manner. This means that all corporate, regulatory, and rule-governed work practices must be followed to assure the safety of personnel and the public. Check with your local authorities to determine what practices must be observed. Discussion with experts and the manufacturer may lead to conclusions as to the root cause, even if the damage makes that difficult. Knowing the values of voltage stress on the insulation, for example, is an important factor to consider if there is evidence of insulation breakdown. Equally important, however, is modeling the voltage stress on the transformer provided by the system. Papers have been written by investigators who have discovered voltage phenomena caused by external system conditions, which result in voltage stresses beyond the capability of the transformer insulation. This example, known as part-winding resonance, has been shown to be the cause of dielectric failure. There is a solution to prevent the occurrence and it becomes the decision of the transformer operator (utility, in most cases) as to whether the solution is economically justified for the risk and consequences.

The design of the transformer and the design of the power system to which it is connected are important aspects of the investigation. The transformer has been designed according to the standards specified in the original purchase agreement. We will discuss the evolution of standards separately.

System studies such as the load flow and short circuit capability of the system may be important to know in the analysis of the failure. Less routine studies to determine transient voltages during system disturbances may be required in some cases. Expertise in these areas should be made a part of the investigation team.

In future articles, we will delve more deeply into the procedures and practices necessary to successfully determine the root cause of a failure. In addition, we will talk about the symptoms of known failure mechanisms.

References

[1] A-Line E.D.S., www.alineeds.com/, Courtesy of A-Line E.D.S., a premier provider of forensic transformer decommissioning

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Wallace Binder has experience in scope development, planning, design, construction, start-up, operation, and maintenance of distribution, transmission and customer utilisation substations, back-up power generation, transmission and distribution lines, and systems.
Wallace Binder has been an active member of the IEEE/PES Transformers Committee for more than 30 years. He has served twice as Chair of the Working Group on Failure Analysis, a position he currently holds. He served as Chair of the Transformers Committee for two years in the late 90's and has contributed to numerous guides and standards developed by the Transformers Committee.
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