Load growth coupled with aging transformers is a disaster waiting to happen

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Advanced transformer condition assessment

Part I

Transformer lifecycle and risk assessment

1. Introduction

I write this article from pure experience, having performed transformer maintenance for many years at a major utility, and then being part of an Electric Power Research Institute (EPRI) team tasked with developing a Predictive Maintenance (PdM) process for transformers and substation components. History and experience have proven that there is no magic bullet for maintaining transformer health. Doing annual or periodic inspections is well worth the effort, but common sense thinking leads me to believe that installing full-time monitoring on critical tier 1 assets is probably the best way to avoid an unexpected failure. But not all transformers merit the same level of attention. Utilities and refineries have many transformers with varying complexity and purpose. I recommend rating each one and assigning them in one of the three following tiers.

Tier 1 transformers will get the highest level treatment; some will be outfitted with full-time Partial Discharge (PD) monitoring and Dissolved Gas Analysis (DGA). Tier 2 and 3 transformers will rarely be chosen for full-time monitoring. The inspection process for all three tiers must be thoughtfully applied. As transformer experts (substation teams), our job is to maintain the highest level of operational capability for our transformers and substations. A coordinated program of online and portable monitoring must be used to make sure that we are doing our part. The criticality of each transformer in your care should be ranked and that ranking used to provide guidance to your PdM team on just what is the correct level of monitoring. The lack of a spare transformer and the lead time to have a new one built (typically 18 to 24 months), delivered on site, and installed is a consideration in the overall process.

The technology advances: Infrared Thermography, Ultrasonic Noise Analysis, Partial Discharge Detection, Dissolved Gas Analysis, and Vibration Analysis are all very high tech and necessary to determine the health of our transformer fleet.

Determining the health of a transformer is a process that can make the difference between a transformer's long life and an early death

ABSTRACT

Infrared Thermography, Ultrasonic Noise Analysis, Partial Discharge Detection, Dissolved Gas Analysis, Vibration Analysis – all these techniques are great stand-alone diagnostic tools; however, when used properly, combining the data obtained through each technique, an incipient fault can be identified long before it degrades the insulation and creates a failure.

This paper will provide guidance in setting up a complete Predictive Maintenance program to be able to provide owners of oil-filled power transformers (4 kV and up), i.e. utilities, refineries, military, mining, etc., with a complete health report and condition assessment of critical oil-filled power transformers and ancillary substation components. The testing described in this paper is done on energized, fully loaded transformers.

Author's vast experience with doing Partial Discharge testing reveals that nearly 80 % of all oil-filled power transformers exhibit some PD. This low level PD activity is not detrimental to the health of the transformer. It is usually a burr or sharp corner that is producing the activity. I consider this just nuisance PD and most times it continues for the entire life of a transformer without a failure related to PD.

KEYWORDS

Partial Discharge, Transformer Condition Assessment, Risk Analysis Tool

In the past 20 years since switching from reactive to predictive transformer maintenance, the advancement of technology has exploded

Each of the listed technologies is proven very effective; however, combining the information from each technology will provide solid answers to those who ask: How much life is left in my transformer? For many years I have dedicated my career path to the development and use of technology to determine the on-line condition assessment of power transformers and ancillary support equipment. Along with determining the remaining life is the issue of an action plan: repair, replace or continue to trend.

In the past twenty-two years since switching from reactive to predictive transformer maintenance, the advancement of technology has exploded. However, the average utility is still doing transformer inspections as it did twenty-two years ago. Consider what information a transformer is willing to give up: it will tell you what is wrong with it if you are willing to listen.

- A transformer makes noise in both the sonic and the ultrasonic range;
- A transformer gives off heat which must be removed during operation;
- A transformer sends signals of impending insulation failure while in operation.

This article will provide knowledge about the latest methods and guidance in setting up a quality program. The goal is to be able to give a complete health report and condition assessment of critical oil-filled power transformers while they remain in service. Remember, the processes described in this paper are done on energized, fully loaded transformers. No clearance or blocking is needed to accomplish these tasks. All tests are completely non-intrusive.

2. Analyzing data from history, coupled with field survey information

Each transformer owner has information and data from each transformer under their care. This data is stored in file cabinets and computer programs and is ready to go to work for you. Mining the data

Table 1. Risk analysis grading tool

Test year 2016	Nemx 1164	Nemx 1164	Xfmr2	Xfmr 2	Xfmr3	Xfmr3	Xfmr4	Xfmr4	Xfmr5	Xfmr5	Xfmr6	Xfmr6	Xfmr7
Criteria	Value	Factor	Value	Factor	Value	Factor	Value	Factor	Value	Factor	Value	Factor	Value
Serial number	6536968		R270131A		G859918P		G859918G		M153429		S1689-01		S1689
Leaks	N	0	N	0	N	0	N	0	N	0	N	0	N
Control wiring condition good	Y	0	Y	0	Y	0	Y	0	Y	0	Y	0	Y
Winding power factor	0.48	0	0.49	0	0.55	-5	0.45	0	0.71	-5	0.44	0	0.45
Oil power factor @ 25°C	0.04	0	0.032	0	0.079	0	0.073	0	0.043	0	0.054	0	0.021
DGA condition code	3	-8	1	0	1	0	1	0	1	0	1	0	2
Full time DGA monitoring	Y	0	N	-5	N	-5	N	-5	N	-5	N	-5	N
Current gas generation - arcing	Y	-10	N	0	N	0	N	0	N	0	N	0	N
Current gas generation - thermal	N	0	N	0	N	0	N	0	N	0	N	0	N
Oil acidity	0.02	0	0.02	0	0.02	0	0.02	0	0.02	0	0.01	0	0.01
Oil IFT	38.9	0	40.3	0	33.5	0	38	0	36.5	0	40.5	0	40.7
Oil dielectric (D877)	36	0	39	0	44	0	34	0	38	0	38	0	44
Water in oil (% Saturation)	3	0	65	-10	11.3	0	64.1	-10	5.4	0	8.4	0	5.9
PD burst interval in waveform	9	0	8	0	9	0	9	0	9	0	9	0	8
Arcing/sparking in waveform	N	0	N	0	N	0	N	0	N	0	N	0	N
Lightning arrester test at full voltage	N	-5	Y	0	Y	0	Y	0	Y	0	Y	0	Y
Full time PD monitoring	N	-5	N	-5	N	-5	Y	0	Y	0	Y	0	Y
Manufacture date	1961		2008		1970		2012		1985		2005		2005
Age in years	55	-28.125	8	1.25	46	-22.5	4	3.75	31	-13.125	11	-0.625	11
Winding temperature (diff. from 55)	26	9	29	9	15	9	17	9	24	9	25	9	26
Highest top oil temp past year	45	0	42	0	38	0	40	0	35	0	45	0	40
Past thermal problems in DGA	N	0	N	0	N	0	N	0	N	0	N	0	N

that already exists, then combining it with current conditions allows us to provide a grade for each transformer. This aids in determining the risk analysis and apply the correct surveillance for each transformer. Once the data is entered into the Excel spreadsheet (Table 1) from your available data source, maintaining the spreadsheet is simple. Data gathered while doing inspections is entered and any changes to the DGA is also entered. The age is changed on all transformers by one click of the mouse. There is no limit to the number of transformers that can be watched simultaneously. Grades are presented numerically as well as a letter, and a secondary grade is also given to indicate the highest possible score achievable when all deficiencies are corrected. The Excel spreadsheet contains formulas built into each cell that do the calculations on the risk of each condition and how it affects the health and life expectancy of each transformer entered on the spreadsheet.

3. Do you think that waiting until a disaster strikes is the time to react?

The **aging of the electrical infrastructure** worldwide is a critical problem that each of you face. There is no way to get around that fact. As aging transformers continue to fail, a new level of awareness of the magnitude of the situation becomes very clear. Load growth coupled with aging transformers is a disaster waiting to happen.

Many transformers fail unnecessarily. Accurate condition assessment and proper care of these valuable assets is needed now more than ever. With the transformer fleet's average age over 40 years and the new transformer fleet having a higher-than-expected failure rate, a proactive approach to PdM is needed. Large power transformers are not off-the-shelf items and must be ordered one to two years in advance. The repair and replacement schedule is critical in most cases.

The crucial nature, age, long lead time, and the interconnection of the grid's electrical system demand that the best maintenance approaches possible are applied to help ensure reliability

I have just inspected a critical 500 kV transformer that is sitting next to a failed transformer that is still smoldering. The operating transformer has partial discharge and arcing confirmed by DGA and by a specialized tool for doing online partial discharge measurements. It also captures arcing from the component under test. Using hind-sight, these transformers should have been outfitted with on-line monitoring which would have seen the catastrophic fault prior to the failure. This is a very serious condition which could result in the loss of electric power to a major portion of a small city.

The crucial nature, fragility, age, long lead time for major components, and the interconnection of the grid's electrical system demand that the best maintenance approaches possible are applied to help ensure reliability.

4. Transformer life cycle management / risk management

Determining the condition, health and risk assessment of a transformer is a process that can be the difference between a transformer's long life and an early death. Certain random failures can occur any time and with little or no warning, but as a transformer ages, there will be measurable warning signs that somehow foretell the cause(s) of degradation or impending failure. The insurance industry states that insulation failure is the number one cause of transformer failure. So how do we determine the insulation quality while these transformers remain in service?

Certain random failures can occur any time, but as a transformer ages, there will be measurable warning signs that somehow foretell the cause(s) of degradation or impending failure

Examine what you are doing now!

A **typical inspection** program includes the following:

- Visual inspection
- Dissolved gas analysis
- Infrared outside control
- Offline electrical testing

Note: Most utilities are doing this inspection process, which has not changed in the past twenty years, or more.

An **enhanced program** could include these additional components:

- Partial discharge monitoring and analysis (portable and on-line)
- Vibration analysis (determine core and coil assembly tightness)
- Sound level measurements (precursor to looseness)
- Grading method (transformer assessment and ranking tool)
- Template building (tier assignment done here)

Note: Adding these to your existing program could greatly reduce the unexpected failure rate.

Template building is a process where each transformer gets its own criterion sheet. A team of substation engineers gathers information on each transformer and decides what type of diagnostic data should be collected based on the criticality of each transformer. Tier assignment is done at this time. Tier one transformers are considered critical and should get the most attention. Tier two transformers are important but have redundancy and spares. Tier three transformers are least important and could run to failure without major upset of the grid.

Combining data from several techniques will provide information

Very rarely will a failure occur without first revealing some small change that is detectable utilizing one or more tech-

If the source of the fault is located in an area where its sound reaches the tank wall, acoustic sensors could triangulate the exact spot of the fault

niques. Having stated this, information provided in this paper will direct and assist the reader starting an inspection process or expanding your existing PdM program.

This paper is designed to show the benefits of doing a complete Transformer Condition Assessment (TCA). Combining the data from various techniques will provide insight and understanding of often subtle, pre-failure signs. In addition, a complete TCA will provide an as-accurate-as-possible gauge of the health of the transformer's subsystems, including: pumps/cooling system, Load Tap Changer (LTC), De-energized Tap Changer (DETC) and lightning/surge arresters.

Partial Discharge (PD) is unwanted electrical activity. PD is similar to corona and occurs at high voltage sine wave peaks. Most low-level PD activity is load-dependent. As the load increases, the voltage decreases. When the voltage decreases, the PD will decrease or disappear completely, and then return when the voltage returns to full value.

My experience with doing PD testing reveals that nearly 80 % of all oil-filled power transformers exhibit some PD. This low level PD activity is not detrimental to the health of the transformer. It is usually a burr or sharp corner that is producing the activity. I consider this just nuisance PD and most times it continues for the entire life of a transformer without a failure related to PD. However, when true insulation breakdown occurs, both indicated and worsened by the PD, and reaches a point that it threatens the life of a transformer, a decision must be made to remove the transformer from service.

Because PD is present in so many transformers, knowing the present condition of each transformer under your care is critical. Without systematic TCA, there is insufficient information available to confidently decide when to take appropriate action. In a quest to determine unwanted activity, data can be gathered at a moment in time, like taking a snapshot, or continuously over 24 hours or more, like making a movie. Movies generally tell a more complete story.

By adding the enhancing technologies to your TCA process, major failures will be averted. Major money will be saved, and a major safety feature will be built into every visit to the high-voltage transformer yard.

Detecting acoustic and electrical problems on energized equipment

The following PD test described is used to determine the severity of an electrical fault using the burst interval of the PD pattern captured by the High Frequency Current Transducer (HFCT). Then, if the source of the fault is located in an area where its sound reaches the tank wall, acoustic sensors could triangulate the exact spot of the fault. Fault sound reaches the tank wall about 90 percent of time. The remaining 10 percent of faults are too deep within the core and coil assembly, and the sound cannot be detected externally. In these cases, at least the severity of the fault and the fact that the transformer will require some work deep within the windings is determined.

Acoustic tests have been used for many years to detect and locate partial discharges in power transformers, but the addition of the HFCT installed on the case ground of the subject transformer makes the process complete. It is more difficult to determine if a problem in an oil-filled transformer is related to mechanical or electrical malfunction utilizing acoustic sensors alone. Partial discharge testing using both acoustic sensors and an HFCT makes the determination easy and increases the protection factor for these utility industry assets.

Figure 1 shows acoustic and electrical PD activity obtained simultaneously. The

Asset managers need to know what to do and when to do it to be able to extend transformer life or avoid impending failure

Figure 1. Data showing classic partial discharge: the top screen shows Acoustic Emission (AE); the bottom screen shows Electromagnetic Interference (EMI)

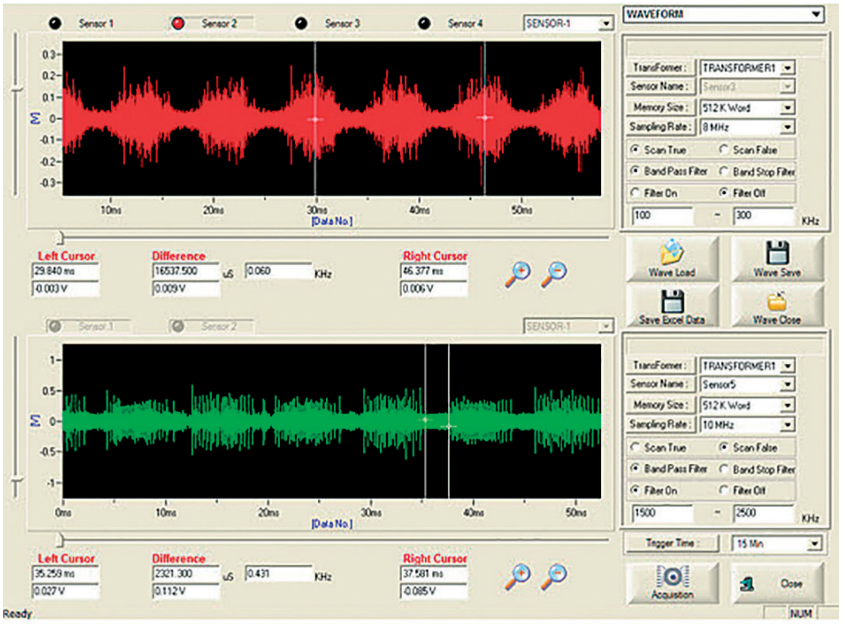

Figure 2. The wave data indicating PD with a burst interval of 2.3 ms

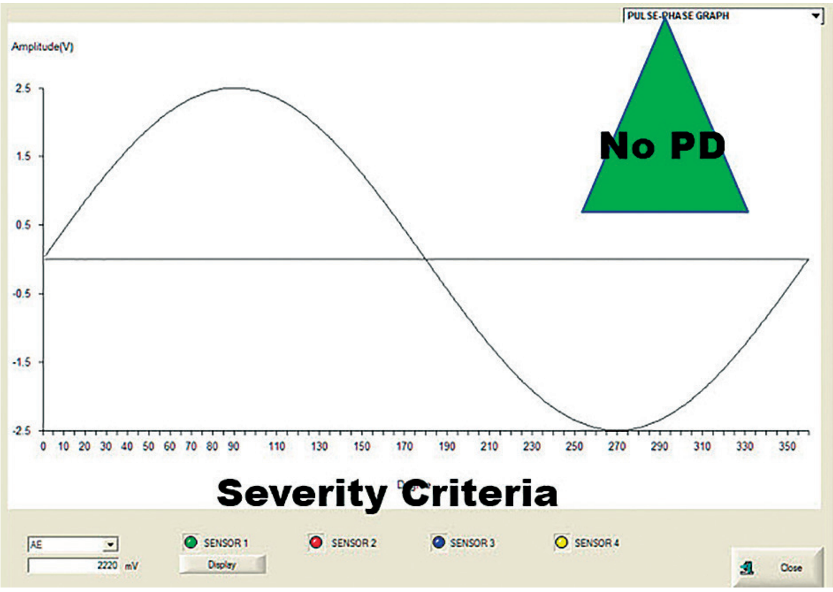

Figure 3. Pulse Phase Graph showing no PD activity

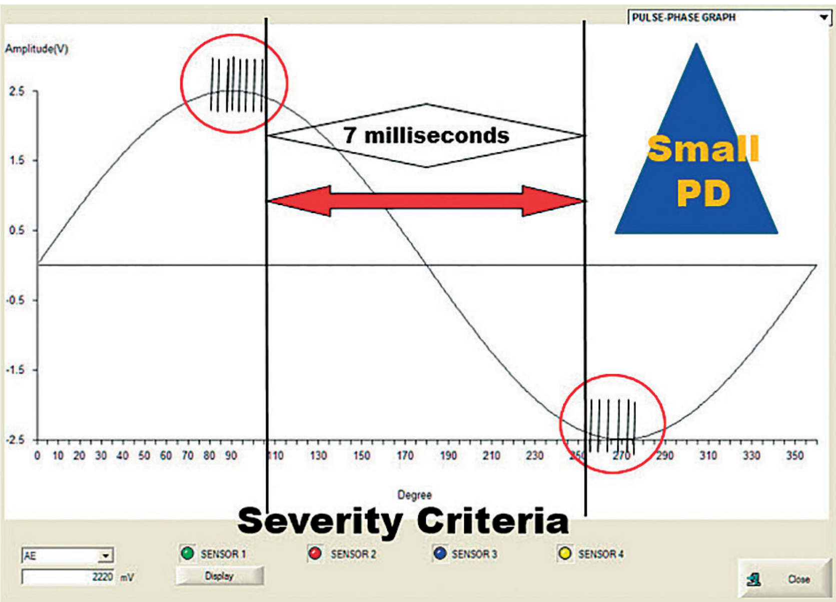

Figure 4. Pulse Phase Graph showing small PD activity

top portion of the screen shows recorded acoustic sensor data, and the bottom shows data from the HFCT. In the example presented by this figure, the spacing of both the Acoustic Emission (AE) and HFCT sensors is 16 milliseconds, which is one full sinewave. The test equipment used for this data collection is the TP500A from PowerPD. The TP500 software has built-in bandpass filters which enable the user to filter out noise and pinpoint the PD, arcing or sparking. Source location of the fault is done using the acoustic sensors.

Severity criteria

Asset managers need to know what to do and when to do it to be able to extend transformer life or avoid impending failure. The ability to trend the deterioration process aids the asset manager in deciding when to take action.

Figure 2 shows acoustic and PD data measured for amplitude and duration. This is easily trended by comparing subsequent test results under similar conditions. The top window in this figure shows the AE bursts with sensor #2 (red) being closest to the source. The bottom window shows the PD burst captured from the case ground lead using the HFCT.

The signature captured by the HFCT, in the bottom portion, indicates a severe case of PD. The spacing between the end of one burst and the beginning of the next burst, called burst interval, is getting dangerously close to 2 milliseconds, clearly indicating a failure is imminent. Burst interval is critical information in determining the severity of PD.

Going deeper into the burst interval (60 Hz/milliseconds)

A review of test results for acceptance is performed using the following criteria based on burst interval:

- 8-7 milliseconds: satisfactory (many times 7 to 8 millisecond burst is found and is a non-damaging PD)
- 6-5 milliseconds: engineering review and evaluation needed
- 5-4 milliseconds: consider removal from service in near future
- 3-2 milliseconds: unsatisfactory, make plans to remove and repair now;

There are times when the DGA is indicating PD, but it is not possible to get any PD to be active until 110 % voltage is reached. Once the PD begins, it will drop off when we back down to the rated voltage

experience shows that 2 milliseconds is the critical point for catastrophic failure

- <2 milliseconds: removal from service, danger of catastrophic failure

Testing at repair facilities allows you to select the voltage you wish to use, anywhere from 50 % to 150 %. There are times when the DGA is indicating PD but it is not possible to get any PD to be active until 110 % voltage is reached. Then the PD will begin, but it will drop off when we back down to 100 %. When the PD begins to deteriorate the insulation, the activity will increase at a lower voltage. If there is a small insignificant nuisance PD, it will have a burst interval of about 8 milliseconds. As the insulation deteriorates the PD begins at a lower voltage and stops at a lower voltage. PD is a voltage related event. The Pulse Phase Graphs, shown in Figures 3 to 6, indicate varying severity of PD based on burst interval and not amplitude. As the PD occurs closer to the zero voltage crossing, the risk of failure increases. My experience has been that 2 milliseconds is the critical cut-off point prior to a catastrophic failure. The charts in Figures 3 to 6 are hand-drawn to show examples of burst interval.

The wave data in Figure 2 indicates a PD with a burst interval of 2.3 milliseconds (ms). It was recommended to remove this unit from service.

Part II of this paper will discuss lightning/surge arrester testing and vibration and sound level analysis, presenting the case studies and final conclusions.

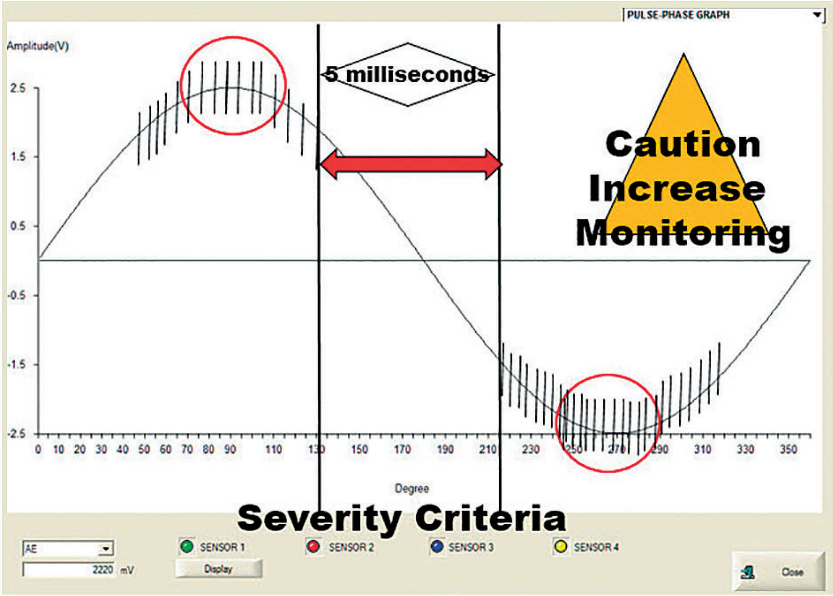

Figure 5. Pulse Phase Graph showing increasing PD activity requiring caution

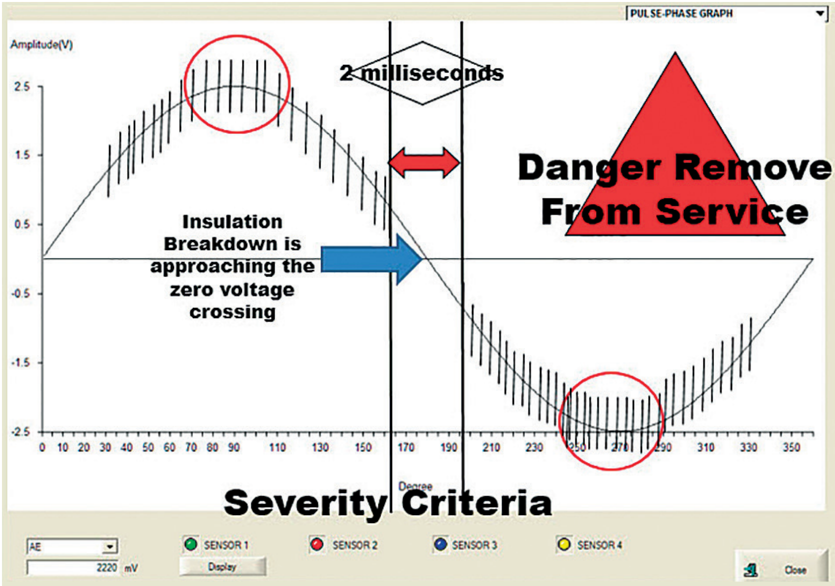

Figure 6. Pulse Phase Graph showing dangerous PD activity

Author

Jon L. Giesecke is an expert in combining technologies used in in-service inspection of high voltage oil-filled power transformers and substation diagnostics, with over 20 years of experience in transformer/substation predictive maintenance and over 25 years in substation electrical maintenance. Prior to forming JLG Associates LLC in 2006, he was employed by EPRI Solutions as a senior project manager in the Substation Predictive Maintenance business area. Mr. Giesecke is also an ITC level III thermographer and has instructed at the FLIR ITC training center. He served on the board of directors of the International Society of Professional Thermographers, Inc. (ISPoT), and chaired the ethics committee. He was also responsible for PdM template development for fossil and nuclear applications. His career in electrical maintenance spans over 30 years with Exelon, formerly Philadelphia Electric Company. During his career with PECO, he held many positions, from helper to foreman, including 4 years of Doble testing, 2 years in outage planning, 2 years as training coordinator for the nuclear group, and 2 years as turbine/generator foreman.