Substation Transformer Condition-Based Maintenance (CBM)
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Executive Summary

This document illustrates two important ways you can use the PI System to:

- Implement Condition-Based Maintenance (CBM) on substation transformers
- Set up a simple Computerized Maintenance Management System (CMMS), which can guide the development of a more complex, specialized system

It is worthwhile to invest the time to implement these measures, since they could help prevent catastrophic events with a transformer.

Introduction

The goal of this document is to illustrate how to prioritize and optimize resources and reduce downtime by implementing a modern maintenance strategy that is condition-based rather than calendar-based. The PI System makes this possible by providing real-time data to monitor the condition of assets on a day-to-day basis and determine what maintenance needs to be done, and when to perform it. CBM means performing maintenance not at scheduled times, but only when specified indicators show signs of decreasing performance or upcoming failure. CMMS is intended to help decision makers do their jobs more effectively (for example, determining which machines require maintenance and in what order).

These measures not only provide a higher level of situational awareness but also enable you to produce reports and documentation giving details and insights on maintenance activities.

Figure 1 - P-F Interval Chart
The P-F Curve chart is one of the most important tools for a reliability centered maintenance plan. It demonstrates the relationship between machine breakdown, cost, and how it can be prevented where P is potential failure and F stands for functional failure. By extending the P-F Interval, CBM methods provide the earliest possible prediction of equipment failure with maximum benefit: minimum production loss, reduced maintenance labor and materials costs, extended equipment life, and reduced capital expenditures. In other words, it allows for the detection of beginning of failure (P) so the asset can be serviced before a full functional failure (F).

High-Level Solution

Several examples of transformer monitoring are presented here, one in each of the following sections, with a technical explanation on how to implement them in the PI System. Finally, at the end of the document a simple CMMS that ranks assets by health status is introduced for asset management prioritization.

It is important to emphasize that these can be very low-effort initiatives. At the beginning of each use case, a list of the required attributes and data is presented. It should only take a few minutes to model them in AF, even without an existing tree or hierarchy in place.

We will start with a very common (and simple) use case focused on transformer top oil temperature followed by a similar approach but using dissolved gas analysis data instead. Then, load tap changes are analyzed for excess usage and an interesting use case relating weather data and fan running status is presented. The last part of the document works on an example of how to use Excel and Datalink together to convert a transformer load curve into a load duration curve. Finally, a simple CMMS solution in PI is developed as a started point for more advanced future implementations.

Transformer Operations

A transformer performs a very simple function of stepping down voltage and stepping up current. AC power travels efficiently with high voltages and lower current levels. Power is a combination of voltage x current (P = IxE) or Power (P) is the product of current (I) times voltage (E). Units are confusing but power is usually expressed as KVA or thousands of volt amperes, again a measure of Volts * Amperes.

As the source of a power plant voltage is stepped up, and then as it moves through the T&D system, voltage is stepped down and current stepped up, to maintain the power level. This is accomplished using windings on both sides of the transformer. The high-side, or primary, windings are the incoming power, the secondary windings are the output side. There may be multiple secondaries on a given
transformer, that is, two or more outputs, usually at different voltage levels. So, a 138kv/69kv transformer would convert 138kv voltage to a secondary of 69kv.

This transformation creates a lot of heat based on the amount of power transferred. The windings are kept in a vat of oil to maintain temperature and minimize winding insulation damage. Some transformers have additional cooling systems such as cooling fans. The windings are in oil (usually some form of mineral oil) and also may have a large oil tank above the windings where the oil is transferred to and cooled. The oil is either manually sampled and tested in a lab on a regular schedule (such as annually) or it might be analyzed continually using an on-line device. These devices normally test for certain gases that indicate oil condition or winding wear and degradation. Water in the oil degrades the oil’s ability to perform its function and is often described as moisture content.

Also note that AC power is transmitted in 3 phases and transformers are usually three-phase devices, although some large, older transformers may be single-phase (there will be 3 transformers for one circuit in this case). Transformers have a very long life span, typically 60 to 80 years. They are very simple yet expensive items and they are critical to T&D operations. It’s not only their replacement costs that’s important, it’s also the cost to replace, the lost power during an outage, the potential environmental costs if there’s a loss of oil or fire. When transformers fail, they usually fail catastrophically, and we hope there’s no one around when they fail.

Transformers have operating limits based on power transferred and are rated for normal and emergency operation. Emergency ratings indicate the higher-than-normal range where the transformer can operate for short periods of time, given that it is in good health. Understanding how much power has been transferred over time relates directly to asset life. IEEE and others have published standards to calculate remaining transformer life.

**Oil Temperatures**

The oil in a transformer suffers continuous degradation because of the electrical, thermal, and mechanical stresses it is subjected to in operation. Transformer oils are a key part of the insulation system and play a vital role in assessing equipment integrity. Regular oil checks are essential to avoid sudden failures.

The first, and simplest, example focuses on using asset analytics to compare current oil temperatures to preset limits and send out email notifications with custom criticality levels. The idea is to send warning emails only when the temperature is within an operating range, while a high importance notification would be triggered after the temperature reached and stayed about a specific threshold it for a given amount of time, such as a half hour or fifteen minutes.
The transformer element should have a temperature attribute with “limits” traits configured. To configure this, right click on the attribute and select “Limits.”

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Oil Temperature</td>
<td>35 C</td>
</tr>
<tr>
<td>Hi</td>
<td></td>
</tr>
<tr>
<td>HiHi</td>
<td>100 C</td>
</tr>
<tr>
<td>Lo</td>
<td>5 C</td>
</tr>
<tr>
<td>LoLo</td>
<td>0 C</td>
</tr>
<tr>
<td>Target</td>
<td>35 C</td>
</tr>
</tbody>
</table>

Figure 2 - Oil temperature attribute and traits

These limits should be provided by the equipment manufacturer or be available through an asset management system. Now let’s create an Event Frame that will trigger on temperatures reaching “Hi” and “HiHi” with different levels of severity as can be seen below. Notice that those conditions must be above 15m and 5m respectively before creating an Event Frame.

<table>
<thead>
<tr>
<th>Event Frame Template</th>
<th>Hi High Temperature Template</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Expression</td>
</tr>
<tr>
<td>StartTrigger2</td>
<td>Top Oil Temperature &gt; Top Oil Temperature</td>
</tr>
<tr>
<td>EndTrigger</td>
<td>Type an expression (optional)</td>
</tr>
</tbody>
</table>

Figure 3 - Oil temperature event frames

Finally, a Notifications template is created for the analysis following the same rules as the event frames. Notice that a custom email format is created to make sure to include the variable “Severity” in the email as can be seen on the figure below. This allows for one template to cover many levels of alarming.
**Dissolved Gases and Moisture**

DGA has gained worldwide acceptance as a method for the detection of incipient faults in transformers. It measures concentrations of various gases dissolved in the transformer oil due to decomposition of the same and its paper insulation. Some devices provide readings in real-time and the PI System can leverage those capabilities to monitor and alert any rising issues.

Although not every transformer will have Dissolved Gas Analysis (DGA) telemetry, this is a valuable and yet simple to implement use cases and should always be done when possible. The idea behind it is simple: using Asset Analytics, compare current levels of dissolved gasses (parts per million) with given limits provided by IEEE (these recommendations are publicly available online) and monitor them for reaching pre-determined limits and high rates of change. Below is an example of measurements coming from a wireless DGA device modeled in AF with IEEE limits configured as traits:

*Hint: When attribute traits are configured (such as the “Limits” mentioned in this example), other applications have easy access to it, providing a richer user experience. PI Vision, for example, can auto configure multistate levels from traits!*
The following two figures show the performance equation syntax to test the two use cases: first, the current levels of a gas against its preset limits (configured as child attribute traits). The second tests for how quickly the gas contents are increasing in the oil.
Although only hydrogen was used in this example, it is important to implement the same logics with all the other gas concentrations available from the device, including moisture content in the oil.

**Hint:** Use multiple start triggers combined with “severity” on Event Frames to combine multiple alarms into one. That way you will also only need one Notification template!

**Load Tap Changer**

A load tap changer (LTC) is one of the most maintenance-intensive pieces of a power transformer. It is known that many transformer failures are related to aging effects of the on-load tap changer contacts.

Two use cases involving LTCs will be presented:

- A unit has not gone through its neutral position in a given time range, 7 days for this case.
- Capture a high number of tap changes within a given time range, 24 hours in this example.

This example is a great candidate for leveraging Event Frames and BI reporting applications such as Microsoft PowerBI for visualization. LTCs usually have, at a minimum, two data streams: a status (or current tap position) and a counter to keep track of how many times it has changed.

The figure below shows commonly found measurements for an LTC:

<table>
<thead>
<tr>
<th>Category: LTC</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily TAP Count</td>
<td></td>
</tr>
<tr>
<td>Hi</td>
<td>50</td>
</tr>
<tr>
<td>Last Neutral Position Date</td>
<td>5/3/2017 12:00:00 AM</td>
</tr>
<tr>
<td>Position</td>
<td>4</td>
</tr>
<tr>
<td>Total TAP Count</td>
<td>1498201200</td>
</tr>
</tbody>
</table>
For the first use case, an auxiliary attribute (Last Neutral Position Date) was created to keep track of the last time it was at neutral position. This avoids the need to request 7 days’ worth of data every time a new value arrives and the performance issues that might result. The figure below shows how to capture the current date and store it in that auxiliary attribute if the value for Position is ZERO.

![Figure 9 - Auxiliary attribute to store last neutral position date](image)

The second use case is more straightforward and only requires a simple comparison between current and last value at 24 hours ago.
Figure 10 - Event frames template for capturing excessive number of changes

The analysis only needs to run once a day, at the end of the day, to check if the number of operations has exceeded the pre-configured thresholds. This can be changed at the Event Frames template. Simply change the “scheduling” option to “Periodic” and change it to “Daily” at 12AM.

Below is a PowerBI report showing the number of transformers where the number of changes exceeded the pre-set threshold. The results are shown by region, month and season of the year. The report also includes a table populated with the worst offenders.
**Hint**: Use an auxiliary tag to store values whenever a calculation needs to request large amounts of historical data from the PI System. That allows for scalability and faster calculation times.

**Fan Status and Weather**

The failure of a transformer fan can lead to more serious consequences such as the overheating of the equipment. Actively monitoring the status and run hours of a fan can increase its life span and provide other benefits.

Combining fan statuses with current temperature leverages data from different sources into a single analysis. Comparing fan status (usually coming through SCADA) and ambient temperature (often collected from an online source or external database) enables you to identify units that are not running as they should. The goal is to check for fans that are running unnecessarily during a cold day or not running when temperatures are high.
Assume the substation ambient temperature is in a relational table for this example. The table name is "Weather". We need to filter our query by "Station Code" and, since we want the current temperature, also by the column "Measurement" to reflect that. The SQL query generated and stored at the configstring will look something like:

```
SELECT value FROM Weather WHERE [Station code] = [@Station code] AND Measurement = 'temp' ORDER BY Timestamp' DESC
```

**Hint:** Order by the column that represents the timestamp and make sure to “ORDER BY” to get the most recent value.

Figure 13 - Fan status event frames template XXX

The screenshot above shows the described logic implementation in PI System Explorer. Note that it breaks it down into two variables and uses either as a trigger to start Event Frames. (A similar use case would be to use oil temperatures instead of ambient temperature.)
Load Duration Curve

A load curve indicates load variations and their durations in chronological order for some time interval, such as a day or month. Arranging the durations in order by decreasing load size, however, creates a load duration curve. (The duration for the highest load is on the left, with durations for progressively smaller loads to the right.)

Plotting a transformer’s MW and MVAR loads over a period of time allows engineers to visualize the amount of time the equipment was overloaded. This allows planners to quickly and objectively prioritize infrastructure reinforcement options according to greatest overload risk and duration.

To create a load duration curve for this example, use PI DataLink in Excel and choose the “Calculated Data” function. Keep in mind that, due to the nature of time series data, if a value remains constant within its set deadband only a few values will be archived for that time period. In contrast, other busier time periods will yield many more archived values. This inconsistency could potentially create problems when sorting the data, and for that reason we want to bring evenly spaced values into the spreadsheet.
Select the element and attribute holding the transformer’s load data (in MW) and import it to the spreadsheet. The example uses a time range of 24h, a 30min interval, and “Average” for calculation mode. The screenshot above shows the timestamps and original data in columns A and B. Column C is the result of sorting the values from column B and was produced by selecting “Sort” by “Largest to smallest” from Excel's data ribbon.

In the following chart, the orange curve indicates the 24 hour transformer load, and the blue curve is the calculated load duration curve.
Hint: The use of an interval on the calculated data PI DataLink query will return evenly spaced data. This will prevent any problems when sorting the data in this example.

Condition Assessment System

The simple condition assessment system in the following example involves calculating an asset health score for each item of equipment and using those scores to find, prioritize and automate maintenance orders. This example serves as illustration only and by no means attempts to provide a solution to the problem.

The following screenshot contains an equipment scores report (from a successful PSE&G implementation of a CMMS project) to help prioritize maintenance and resources:
The scores for the items are derived using a combination of an alarm weight system with its aggregation. Scores are later sorted and used for prioritization. In summary, a number is given to each alarm type and that is used as its score. For the example of the top oil temperature use case in “Oil Temperature,” the “Hi” alarm has a score of 1 while “Hi Hi” is weighted at 3. (Similarly, the severity status for event frames (such as warning, major, critical) can be used to assign different weights.)
These equipment assessments and corresponding scores make it possible to develop an overall aggregation (shown here as the “Overall Asset Health” attribute) as a general asset health score. A rollup analysis aggregates scores from individual pieces of equipment in a substation into a general health score for the entire substation.

Figure 18 - Asset health score roll up analysis

PI Vision 2017 has a new Asset and Event Frames table symbol that can be filtered. For instance, you could create a list showing only assets that are in alarm or a table with all the open Event Frames for an item of equipment.

Figure 19 - Asset table - Filtered list

Hint: A flat hierarchy (in complement of a main tree) is a good idea for implementing equipment-based “roll ups” where the aggregation needs to cover all units, no matter where they are!
Business Benefits

OSIsoft has had several customers implement the aforementioned use cases over the years with great success. The data needed should already exist; it is just a matter of spending a little time to model it to be most useful for your operation and ensure that it can be leveraged by PI System analytical tools to automate this alarm-based CBM project. Just one prevented transformer failure pays several times over for the time and effort spent on the implementation of these use cases.

Call to Action

OSIsoft is here to help. If you feel like you need help please reach out to us.

Don’t have the expertise? We offer many classes for all levels. You can even have a custom class delivered at your location and using your own system!

Need help getting started? Why not have a workshop with a field engineer and a center of excellence engineer to lead the way on this endeavor!

How about questions around configuring analytics or what other users in the industry deal with a problem? You got it! Here are a couple of great resources for that:

- The OSIsoft Community on PI Square is a great place to ask questions and troubleshoot problems together. Also, all the previous discussion are available: [https://pisquare.osisoft.com/](https://pisquare.osisoft.com/)
- And here you will find the T&D users group with forums related to the industry and announcements focused on customers like you: [https://pisquare.osisoft.com/groups/td](https://pisquare.osisoft.com/groups/td)

Following are some customer presentations worth taking a look at for a better and deeper understanding of the CBM use cases mentioned in this paper:

- PSE&G (2016 Users Conference - PSE&G Asset Maintenance and Condition Assessment)
- Fingrid (2016 EMEA UC - Fingrid: Developing Power System Operations)
- ComEd (2014 T&D Industry Session - ComEd: Trusting the Data: Analytics and Visualization)
About OSIsoft, LLC

OSIsoft, a global leader in operational intelligence, delivers an open enterprise infrastructure to connect sensor-based data, operations, and people to enable real-time and actionable insights. As the maker of the PI System, OSIsoft empowers companies across a range of industries in activities such as exploration, extraction, production, generation, process and discrete manufacturing, distribution, and services to leverage streaming data to optimize and enrich their businesses. For over thirty years, OSIsoft customers have embraced the PI System to deliver process, quality, energy, regulatory compliance, safety, security, and asset health improvements across their operations. Founded in 1980, OSIsoft is a privately-held company, headquartered in San Leandro, California, U.S.A., with offices around the world. For more information visit www.osisoft.com.