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Pressure optimization of medium-voltage liquid-filled transformers in photovoltaic solar applications

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At Issue

While medium-voltage liquid-filled transformers have been in use for over 100 years in the United States, the use of this equipment in Photovoltaic (PV) solar applications is still a relatively new practice, with the majority of installations occurring since 2008. For this reason, finer nuances of the transformer's operation in utility-scale PV installations are just now being realized. One of the most common issues to date has been nuisance operation of pressure alarms. This technical paper will focus on Eaton's Cooper Power Systems recommendations for optimizing pressure within the transformer in order to minimize nuisance alarms.

History

Historically, medium-voltage transformers in the United States have adhered to the construction and design practices found in IEEE Std C57.12.00™-2010 standard. Within the C57.12™ series of standards is clause 8.9.2 in IEEE Std C57.12.34™-2009 standard, which states that three-phase pad-mounted transformers must be equipped with a pressure relief valve that opens at +10 psig ±2 psig, while re-sealing at +6 psig (minimum). Contrary to the +10 psig pressure relief valve requirement; clause 8.10.1 in IEEE Std C57.12.34™-2009 standard states that "The tank shall be of sufficient strength to withstand a gauge pressure of (+7 psig) without permanent distortion." While transformer manufacturers have the ability to design transformers to meet both requirements, the requirements themselves lead to confusion. This is because the tank could permanently distort above +7 psig, while the pressure relief valve may not operate until +10 psig (or +12 psig with tolerance) which is +3 to +5 psig above the distortion level. To address this, transformer manufacturers often set pressure alarms to operate at +6.5 psig, prior to the transformer reaching the +7 psig permanent distortion level. While this discussion does not resolve the issue of nuisance alarms, it does set the stage for recommendations discussed later in this paper.

As a baseline for this paper, Eaton's Cooper Power Systems standard offering for pressure and vacuum monitoring are Qualitrol® 50-35E gauges in combination with Gems™ PS41 Pressure Switches. Historically, Eaton's Cooper Power Systems has set these alarm points for positive pressure at +6.5 psig and vacuum at -2.5 psig.

Analysis

To get to the root cause of nuisance alarms on transformers in PV applications, Eaton's Cooper Power Systems collected pressure readings from 47 transformers in both the morning and afternoon, coinciding with the times at which the top fluid temperature would be at its minimum and maximum, respectively. All of these transformers were installed in PV solar applications located in the desert. After analyzing the data collected, the conclusion was that transformers in PV solar applications in the desert see a more strenuous pressure/vacuum cycle than a typical utility application transformer, around which the IEEE Std C57.12™ series standards are written.

Depending on the location a transformer is installed on the electrical grid, utility transformers can range from vastly under-loaded to constantly over-loaded. Under-loading conditions may be due to rural loading requirements, load growth assumptions that do not materialize, or utility sizing practices to prevent customer nuisance issues such as "flicker." Over-load conditions are typically a result of unaccounted for load growth after the transformer was installed, such as the widespread adoption of residential air conditioning units since the 1960s. Yet in either case, utility transformers typically operate in a much smaller loading range, such as 20% to 65% in the under-loaded case or 70% to 115% in the overloaded

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case, with respective peak loading levels occurring only once or twice a year due to unseasonably warm weather. By contrast, transformers installed in PV solar applications are subjected to highly cyclical loading, typically 10-14 hours of load followed by 10-14 hours of no-load with swings in ambient temperature as severe as 25 °C in a single day. Both of these conditions can occur simultaneously; the low temperatures coinciding with the period of no-load and the high temperatures coinciding with the period of heavy loading. On sunny days, the daily loading level can reach 110% for several hours and drop to almost 0% loading during the night. The drastic load changes of transformers in PV solar applications cause typical daily pressure swings of +3 to +4 psig within the transformer that are not typically seen in utility transformer applications that are much more evenly loaded. Figure 1 below represents the typical load of a solar transformer. Due to the volume of the fluid within the tank, both pressure and oil temperature lag transformer loading by roughly four hours.

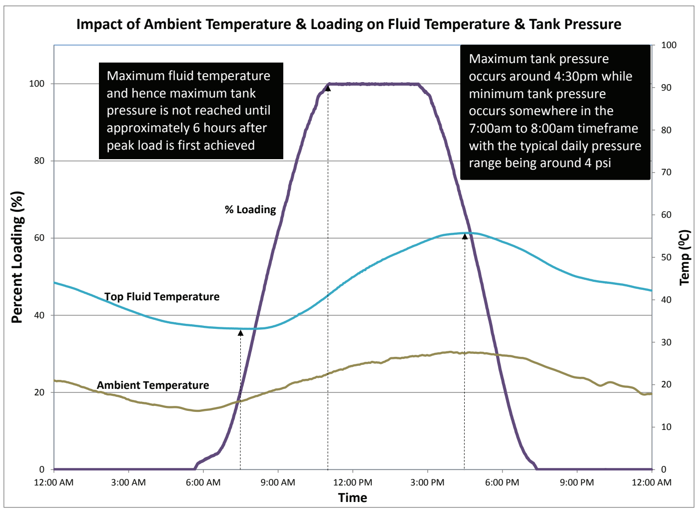

Figure 1. Impact of Ambient Temperature & Loading on Fluid Temperature & Tank Pressure. (Graphical representation is typical of late spring.)

Data

The following data was collected over multiple days in July at a PV solar plant located in the central California desert. The data shows that a typical solar transformer will see a pressure change of +3-5 psig throughout the day.

The example in Table 1 shows an energized transformer with +0.5 psig pressure at 5:00 am in July. This transformer was commissioned in the spring.

Table 1. Pressure Readings After Several Months of Operation, Taken from a Transformer Initially Commissioned at +0.5 psig

Time of Day	Top Fluid Temperature (° C)	Ambient Air Temperature (° C)	Pressure (psig)
5:00 am	40	25	+0.5
4:00 pm	80	46	+4

The example in Table 2 shows a transformer commissioned mid-day in July. The values are from the day of commissioning.

Table 2. Pressure Readings from Unenergized Transformer Commissioned at +3 psig at 12:00 pm. 5:00 pm Pressure Reading Taken Day of Commissioning

Time of Day	Top Fluid Temperature (° C)	Ambient Air Temperature (° C)	Pressure (psig)
12:00 pm	28	35	+3
5:00 pm	80	46	+8

When comparing the transformers in Table 1 and Table 2, it is evident that the starting pressure within the transformer affects the peak pressure. While both transformers experienced similar changes in pressure, commissioning the transformer in Table 2 at +3 psig at 12:00 pm in July caused the peak pressure to rise above the alarm set point (+6.5 psig). Conversely, in operation, the transformer in Table 1 has +0.5 psig pressure at 5:00 am in July, and allows pressure to fluctuate but remain below the +6.5 psig alarm set point. If the transformer in Table 2 was commissioned with a pressure of approximately +1 psig, the alarm trip point would not have been reached and the nuisance trip could have been avoided.

In addition to the commissioning pressure, it should be noted that an unloaded transformer will experience a large increase in pressure due to the large increase in fluid temperature attributable to initial energization. The fluid temperature for the transformer in Table 2 exhibited an increase from 28 °C to 80 °C compared to the transformer in Table 1, which exhibited an increase in fluid temperature from 40 °C to 80 °C. The transformers in Table 1 had a lower change in fluid temperature due to being energized, resulting in a lower overall pressure change.

In addition to time of day, time of year can also cause nuisance tripping of alarms if the pressure is not re-set to account for the seasonal changes in temperature. Below is an example of a typical change from summer to winter in the desert in an energized transformer in a PV solar application:

Table 3. Comparing Seasonal Changes in Transformer Pressure

Time of Day	Top Fluid Temperature (° C)	Ambient Air Temperature (° C)	Pressure (psig)
July, 5:00 am	40	25	+0
January, 5:00 am	10	-5	-2

A transformer will experience lower ambient and top oil temperatures in the winter, and will operate in a vacuum state unless the pressure has been reset from its original commissioning pressure. Considering a +4 psig increase throughout the day, the winter operating range would become -2 to +2 psig, which results in cycling from a vacuum to pressure which can stress welded joints.

Recommendation

The optimum transformer pressure range to maintain throughout the year is 0 to +4 psig. Maintaining this pressure range prevents transformers from cycling between positive and negative pressure, which can cause undue cyclical stresses on the structural members of the tank. Maintaining this pressure range also eliminates nuisance pressure alarms.

Figure 1. Ideal Operating Range (0 to +4 psig) for Transformer Pressure.

To achieve this ideal operating range, Eaton's Cooper Power Systems recommends the following:

- At commissioning, adjust the pressure in the transformer to the pressure in the center column of Table 4 that correlates to the top oil temperature of the transformer
- On a bi-annual basis, adjust the pressure in the transformer to the pressure in the right hand column of Table 4 that correlates to the top oil temperature of the transformer
- Eaton's Cooper Power Systems recommends re-setting transformer pressures in spring between April 15th and May 15th, and in fall between October 15th and November 15th

Table 4. Pressure Settings to Achieve Ideal Operating Pressure Range. Requires Commissioning and Bi-Annual Adjustments

Top Oil Temp (°C) (Per Gauge)	Set Pressure (PSIG) For Commissioning	Set Pressure (PSIG) For Energized Transformer (Energized For a Minimum of 48 Hours)
< 21	-1 to 0	-1 to 0
21-30	0	0
31-40	0	+1
41-50	+1	+1
51-60	Not Applicable	+2
61-70	Not Applicable	+2
71-80	Not Applicable	+3
> 80	Not Applicable	+4

While the ideal transformer operating pressure range of 0 to +4 psig allows for the least amount of stresses on the structural members of the transformer tank, Eaton's Cooper Power Systems recognizes that re-setting transformer pressure bi-annually to maintain this ideal operating range may not be possible for all users. Therefore, Eaton's Cooper Power Systems offers an alternative that allows pressure to fluctuate outside of the ideal operating range, but keeps pressure in an acceptable operating range, -1 to +7 psig, and requires a pressure adjustment at commissioning only.

Figure 2. Acceptable Operating Range (-1 to +7 psig) for Transformer Pressure.

To achieve this acceptable operating pressure range, Eaton's Cooper Power Systems recommends the following:

- At commissioning, adjust the pressure in the transformer to the pressure in the center column of Table 5 that correlates to the top oil temperature of the transformer
- If the transformer has been energized, adjust the pressure in the transformer to the pressure in the right hand column of Table 5 that correlates to the top oil temperature of the transformer

Table 5. Pressure Settings to Achieve Acceptable Operating Pressure Range. Requires Adjustment at Commissioning Only

Top Oil Temp (°C) (Per Gauge)	Set Pressure (PSIG) For Commissioning	Set Pressure (PSIG) For Energized Transformer (Energized For a Minimum of 48 Hours)
< 21	-1 to 0	-1 to 0
21-30	0	0
31-40	+1	+1
41-50	+1	+2
51-60	Not Applicable	+3
61-70	Not Applicable	+4
71-80	Not Applicable	+5
> 80	Not Applicable	+6

The pressure settings recommended above are applicable for all altitude levels, so long as the pressure adjustments are made at the transformer's final location.

If pressure adjustment is required to align with the guidelines in Tables 4 or 5, Cooper recommends the following;

- If current pressure is above the value correlating to the transformer's current top oil temperature in Table 4 or Table 5, operate the transformer pressure relief valve until the pressure is in alignment with the top oil temperature

Figure 4. Pull ring on pressure relieve valve to relieve pressure.

- If current pressure is below the value correlating to the transformer's top oil temperature in Table 4 or Table 5, add nitrogen to the transformer until the pressure is in alignment with the top oil temperature

Figure 5. Add nitrogen via the Schrader valve.

A few days after commissioning, operators should return to the transformer to check the pressure during peak top oil temperature conditions and adjust to the value specified in the right hand column of Table 4 or Table 5 if needed.

If a transformer consistently operates outside of the normal operating range after following the recommendations of this paper, contact an Authorized Transformer Service Center.

Eaton's Cooper Power Systems will continue to monitor and collect pressure data on transformers in PV installations.

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