# The effects of overload on distribution transformers

## The challenges of accurate condition assessment


### ABSTRACT

Southern California Edison removes approximately 30,000 medium voltage transformers from service annually. Approximately 2,000 of these units are subjected to condition assessment testing to determine suitability for re-installation. The challenge in assessment testing lies in accurate interpretation of the measured parameters. This is particularly problematic when evaluating distribution class transformers which are routinely subjected to overloads and voltage transients. With this challenge in mind, Southern California Edison performed a series of energized experiments to simulate specific transformer overload conditions. Transformers were energized continuously at prescribed loads, and insulation quality tests were performed at specified intervals, incrementally documenting the changes in dielectric response and insulation resistance. Upon completion of the thermal cycles, oil quality testing and dissolved gas analysis was performed on all units.



### KEYWORDS

oil, insulation, power factor, dielectric response, loading

## 1. Introduction

In 2016, Southern California Edison (SCE) performed a protocol where 12 distribution transformers were divided into 4 groups and loaded at 90, 112, 125, and 135 % of rated load for a period of 6 months. In 2017, SCE performed a subsequent protocol where 11 distribution transformers were divided into 3 groups and loaded at 115, 125, and 150 % of rated load for a period of 12 months.

Transformers were de-energized every 4 weeks and allowed to cool to ambient temperature. A narrow band dielectric frequency response measurement (NBDFR) was performed on each unit, measuring primary to secondary insulation power factor (CHL) at frequencies ranging from 1 to 1000 Hz. In addition, the primary to secondary insulation resistance measurement was performed at 1000 V DC for a period of 60 seconds.

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## 2. Effects of loading on narrow band dielectric frequency response

NBDFR measurements were performed on an incremental basis for each test specimen. By overlaying the sequential traces, the changes in response could be tracked over time. Traditional insulation power factor analysis utilizes a single parameter for trending insulation condition, specifically the magnitude at line frequency (60 Hz). NBDFR conversely is not a parameter based analytical protocol. A shape analysis of the response trace is utilized to extrapolate information regarding specific components of the insulation system. The frequencies from 10 - 100 Hz are dominated by the influence of cellulose components, while the frequencies from 1-10 Hz are dominated by the influence of mineral oil.

A prevailing paradigm states that if the slope at line frequency is positive, then the insulation system in question is deemed to be in acceptable condition. Although this assertion is valid, it is a significant oversimplification in that the slope at line frequency is dictated by the location of the point of minimum magnitude (trough). As the conductive and polarization losses increase, distortion of the response at low frequencies pushes the response towards the higher frequency end of

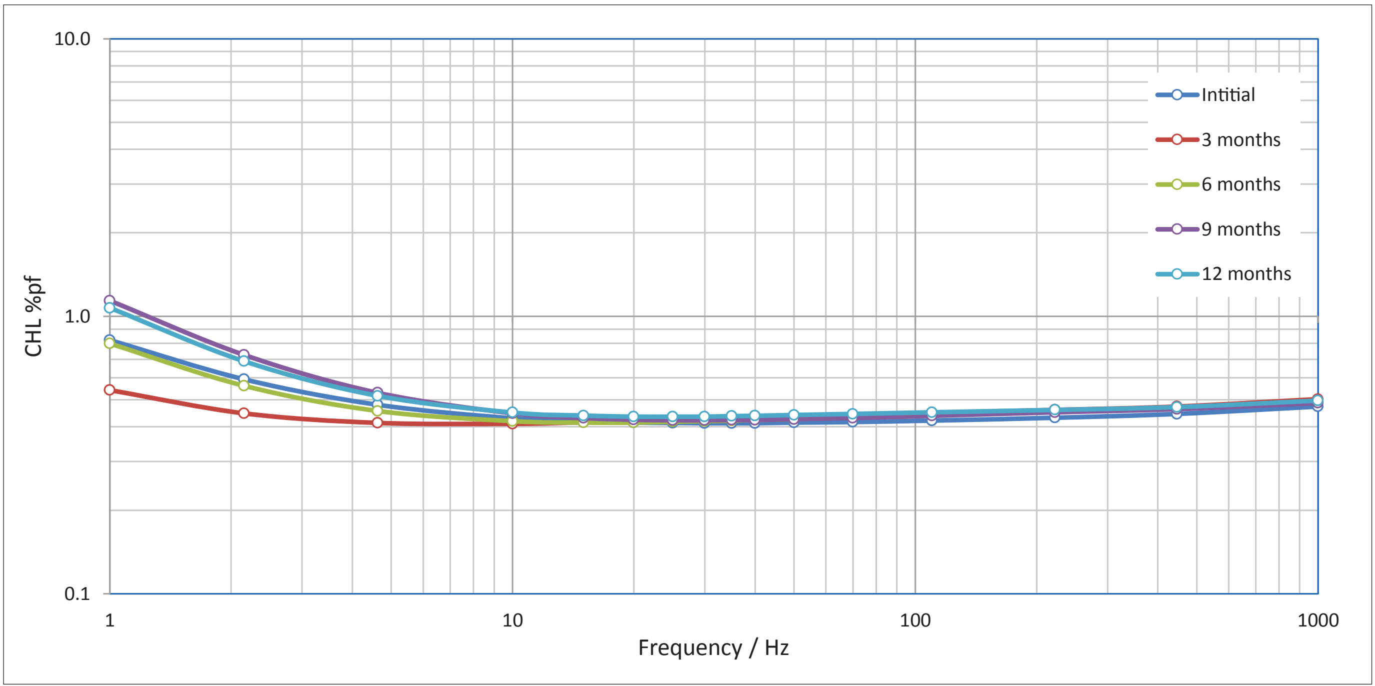


Figure 1. NBDFR for unit energized at 115 % load for 1 year

**Around 2,000 of removed units are subjected to condition assessment testing to determine suitability for reinstallation**

the plot. This creates a relationship where the trough moves as the insulation degrades, enabling trending of insulation condition by monitoring the frequency at which the trough resides [1].

Figure 1 represents quarterly changes in NBDFR for a transformer energized at 115 % of rated load for one year. In this case, the oil undergoes slight degradation which is reflected in minimal changes below 10 Hz. Any changes in cellulose insulation are negligible as seen from 10 - 100 Hz, and magnitude at 60 Hz is essentially unchanged. The trough frequency shift is minor, moving from 10 Hz to 20 Hz.

Figure 2 represents the incremental NBDFR traces for a transformer energized for six months at 135 % of the rated load. In this case, the oil undergoes accelerated degradation which is reflected in progressive changes below 10 Hz. In this case, the magnitude at 1 Hz elevates dramatically from 0.469 to

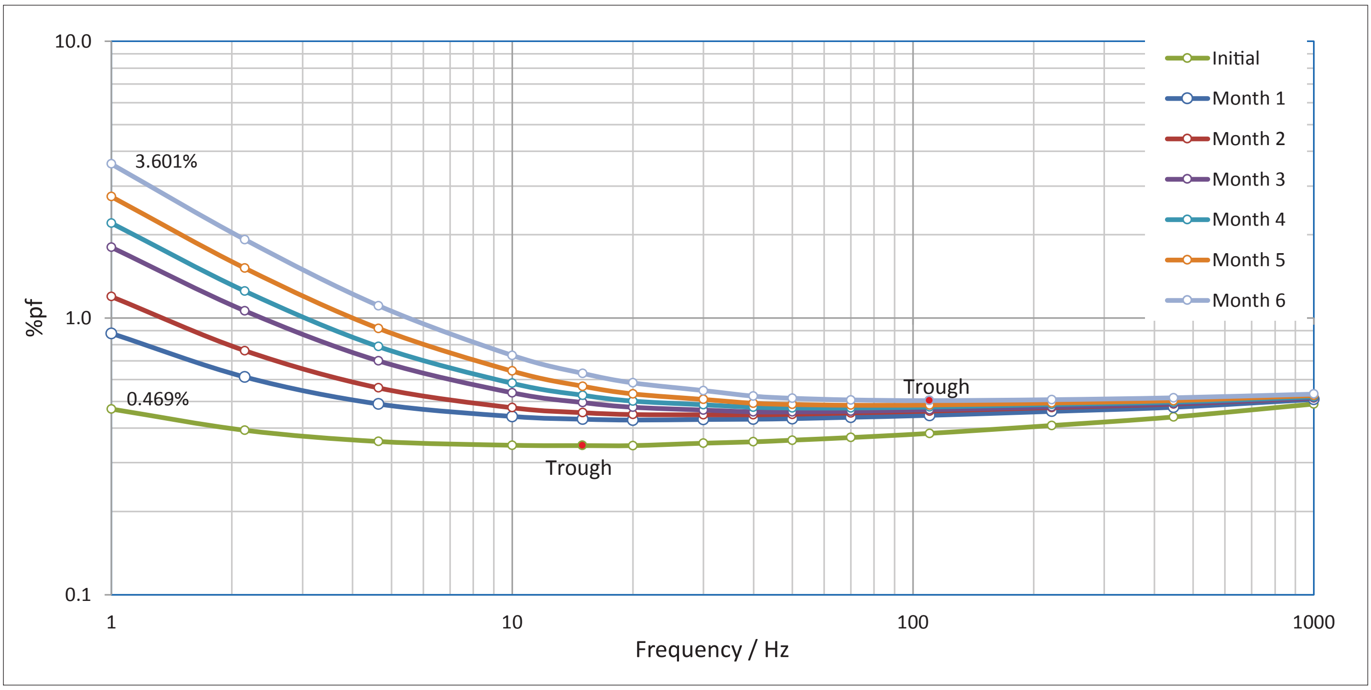


Figure 2. NBDFR for unit energized at 135 % load for 6 months

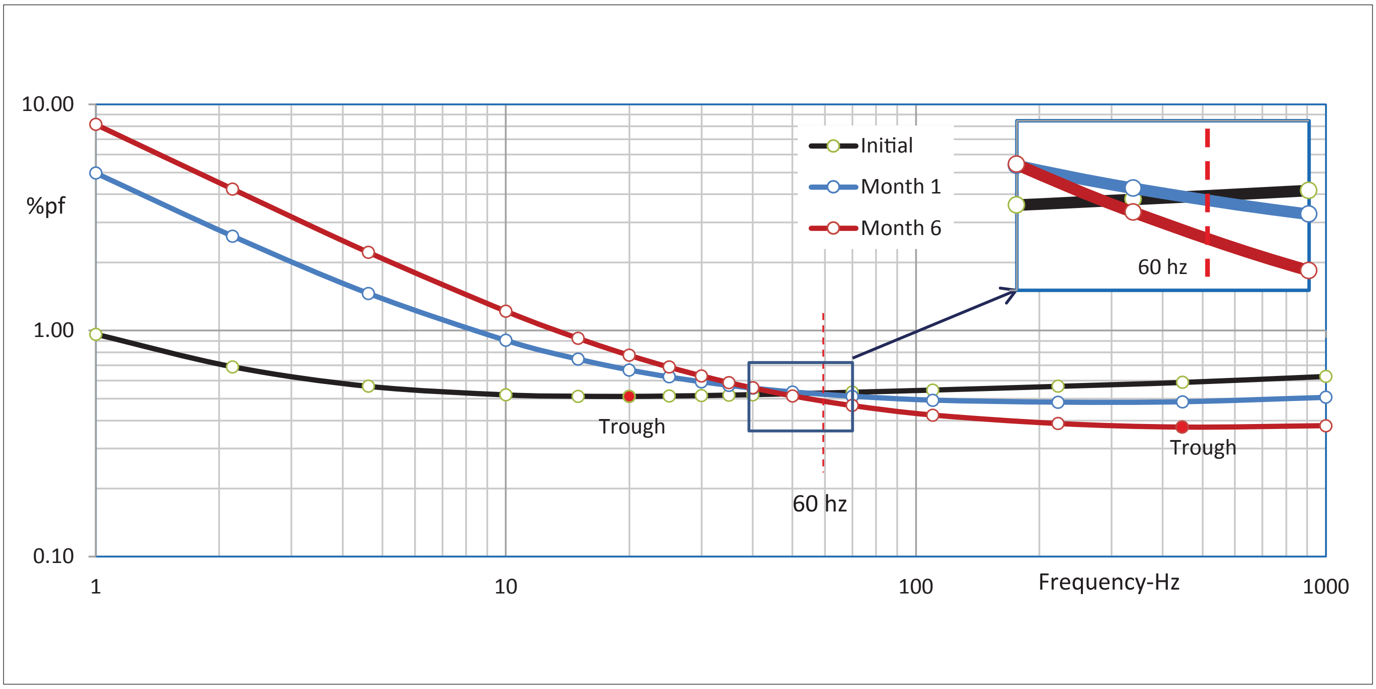


Figure 3. NBDFR for unit energized at 150 % load for 6 months

3.601 %. Changes in cellulose insulation are significant as seen from 10 - 100 Hz. Magnitude at 60 Hz rose from 0.366 to 0.510 %. More significantly, the trough location migrated from 15 Hz to 110 Hz. This is a strong indication that the conductive and polarization watt losses have increased significantly.

**Power factor at 1 Hz is extremely sensitive to changes in conductive and polarization losses, and provides a notification of changes to the insulation system long before they are detectible at line frequency**

At 150 % load the effects of increasing conductive and polarization losses are accelerated further as represented in Figure 3. Magnitude at 1 Hz exceeds 5 % after 1 month and 8 % after 6 months. The location of the trough migrates from 20 to 222 Hz after one month and all the way to 446 Hz at six months. In this case, the movement of the response towards the high frequency end of the plot results in a condition where the magnitude at 60 Hz actually decreases despite an exponential increase in watt losses (see inset diagram in Figure 3). In this scenario, the power factor at 60 Hz is no longer a valid parameter for use in condition assessment [2]. This concretely demonstrates one of the most serious shortcomings in the use of a single frequency in conventional insulation power factor testing.

## 3. Trending of the key response parameters in relation to loading

CHL at line frequency is a common reference for all methods of insulation power factor tests, however, for distribution class transformers this may be an unreliable parameter for the reasons previously outlined. For 95 kV BIL class windings, the frequency at which the trough resides will supersede the 60 Hz magnitude in most cases.

Since the magnitude of winding capacitance dominates the CHL measurement at 60 Hz, a moderate increase in insulation conductivity may have a negligible effect on CHL at 60 Hz. However, as frequency decreases, the capacitive current decreases proportionally, making changes in conductivity increasingly visible. Therefore, while the CHL at 60 Hz may be ambiguous, the power factor at 1 Hz accurately reflects the condition of the oil and the presence of degradation by-products. Power factor at 1 Hz is extremely sensitive to changes in conductive and polarization watt losses, and provides an early notification of changes to the insulation system long before they are detectible at 60 Hz. This parameter provides crucial clarification if trough location and 60 Hz CHL are ambiguous.

As illustrated in Figure 4, the change (Δ) for CHL at 60 Hz after six months is minimal at up to 115 % load. (The Δ CHL values referenced are the averages for each given loading group.) The rate of change increases slightly at 125 % load. When load is increased to 135 % resulting in a temperature increase of approximately 10°C, the change in CHL power factor is significant. At 150 % load, the average winding temperature jumps to 118°C, accelerating oil degradation exponentially. As previously discussed, this creates the conditions where CHL at 60 Hz actually decreases due to severe response distortion.

While magnitude at 60 Hz may be deceptive or ambiguous, the measured response at 1 Hz is a reliable indication of transformer condition. As load and winding temperature increase, CHL at 1 Hz increases exponentially as illustrated in Figure 4. These changes at 1 Hz drive

**Established criterion for the upper limit of power factor at 1 Hz for single phase distribution transformers is 2.0 %**

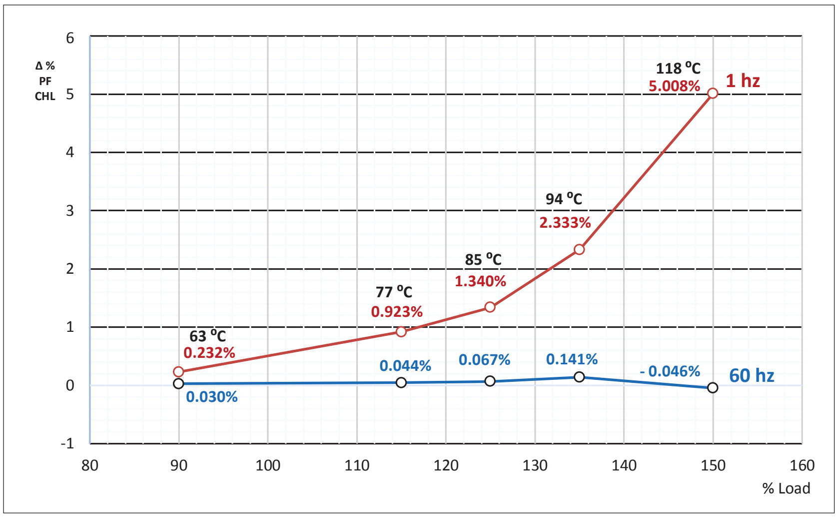


Figure 4. Δ CHL at 1 and 60 Hz vs percent load after 6 months

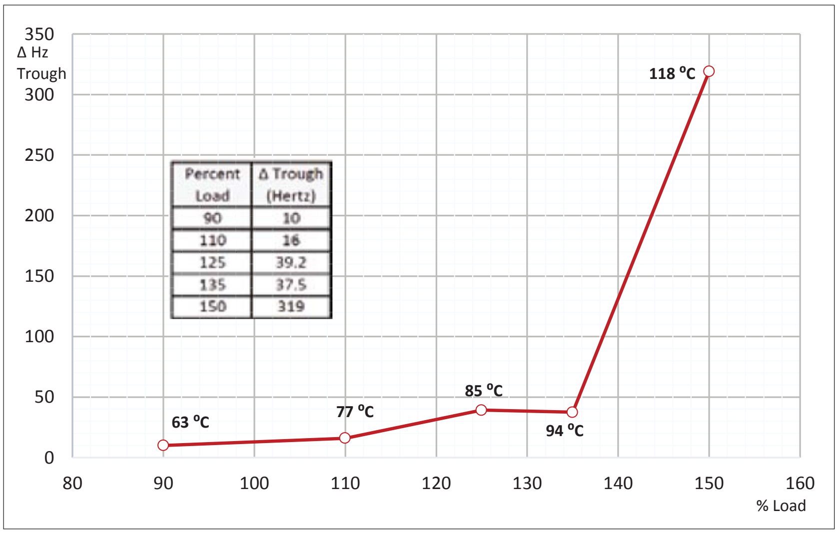


Figure 5. Trough movement expressed in terms of Δ Hz vs percent load through six months

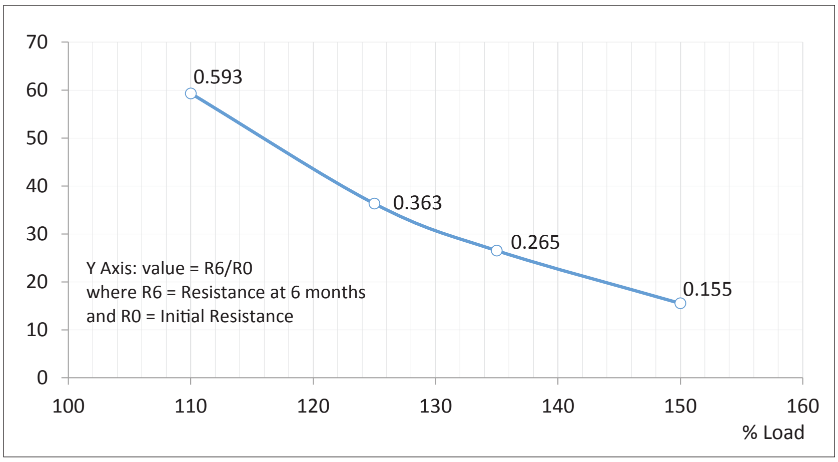


Figure 6. Ratio of 6 month / initial resistance vs percent load

the low frequency distortion and trough movement. SCE is increasingly using this parameter to critically evaluate transformer condition. At this time, SCE has established an upper limit of 2.0 % power factor at 1 Hz for single phase distribution transformers.

The third NBDFR parameter used in condition assessment is the trough location. As seen in Figure 5, the group averages for trough movement (expressed in Hz) are plotted against the percent load. After six months, the trough movement is minimal for the 90 and 115 % loading groups. Migration is significant for the 125 and 135 % groups, indicating that this loading would not be sustainable in the long term. Trough migration at 150 % load indicates very rapid degradation of oil.

## 4. Loading vs decrease in insulation resistance

Insulation measurements were performed from the primary winding to the secondary winding at the end of each monthly heat cycle with the transformer cooled to ambient temperature. The initial and 6 months measurements were corrected for temperature using a nomograph as per IEEE 62- 6.1.5.1. The 6 months resistance values were then divided by the initial values, and these ratios were plotted in Figure 6. Although the group averages correlate very well with the load, it should be noted that measurements performed on a singular basis may be problematic, especially in small kVA units. Due to winding dimensions, insulation resistance values in small units are inherently very high, which may mask issues such as degraded paper or contaminated oil.

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## 5. Oil quality and dissolved gas analysis

The data in Table 1 was collected from 12 transformers energized for 6 months at loads ranging from 90 to 135 % in the 2016 study. Oil samples from each unit were extracted at the end of the heat run and quality tests, along with dissolved gas analysis, were performed. The results from the individual units were averaged by loading group and tabulated as displayed in Table 1.

Dielectric strength of oil trends downwards as load is increased, but the changes are incrementally small, making this a potentially ambiguous indicator. Power factor, on the other hand, trended upward very well with load. Interfacial tension, which indicates the presence of hydrophilic polar contaminates, did not change for the first 3 groups, but decreased noticeably at 135 % load. The acid number, which is an effective indicator of oil degradation, trended upward very consistently as load increased. In the studies performed by SCE, the acid number has proven to be the most consistent loading indicator of all of the oil quality tests. Dividing the interfacial tension by the neutralization number provides a calculated parameter which is an excellent indicator of oil condition. This parameter is known as the Oil Quality Index Number (OQIN) or Meyers Index Number (MIN). This parameter also trended very well as load was increased.

Dissolved carbon dioxide was a very strong indicator of load. Significant increases in $CO_2$ generation were observed as load increased. These levels jumped exponentially when load increased from 122 to 135 %. Carbon monoxide, on the other hand, remained fairly static through 125 % but jumped conspicuously at 135 %. Both of these gasses are commonly associated with the degradation of cellulose.

## 6. Subsequent investigations regarding power factor temperature correction

Temperature correction for insulation power factor can be very problematic, depending on the condition of the transformer. Accuracy of the temperature

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Table 1. Oil data by group

| Quality Test | 90% | 110% | 122% | 135% |
|---|---|---|---|---|
| Dielectric Strength - kV | 50.5 | 51.75 | 50 | 49 |
| Percent Power Factor | 0.0295 | 0.02775 | 0.03725 | 0.0455 |
| Moisture - ppm | 9 | 9 | 9 | 8 |
| Interfacial Tension (IFT) dynes/cm | 28.3 | 27.425 | 27.45 | 23.65 |
| Nuetralization Number (NN) mg KOH/g | 0.014 | 0.018 | 0.0235 | 0.027 |
| OQIN / Meyers Index | 2085.42 | 1539.79 | 1198.73 | 912.358 |

| Dissolved Gases (ppm) | 90% | 110% | 122% | 135% |
|---|---|---|---|---|
| Hydrogen | 0 | 1 | 0.25 | 1 |
| Carbon Dioxide | 2233 | 3813.5 | 4347.5 | 9868 |
| Ethylene | 0 | 10 | 8.5 | 11 |
| Ethane | 0 | 8.75 | 11 | 13 |
| Acetylene | 0 | 0.75 | 0 | 0 |
| Methane | 7.5 | 10.25 | 9.25 | 10.5 |
| Carbon Monoxide | 251 | 282.75 | 277.75 | 373.5 |
| Combustables | 259 | 313.5 | 305.5 | 410 |

| 2-Furfural | 90% | 110% | 122% | 135% |
|---|---|---|---|---|
| ppb | <10 | 10 | 22.25 | 55.5 |

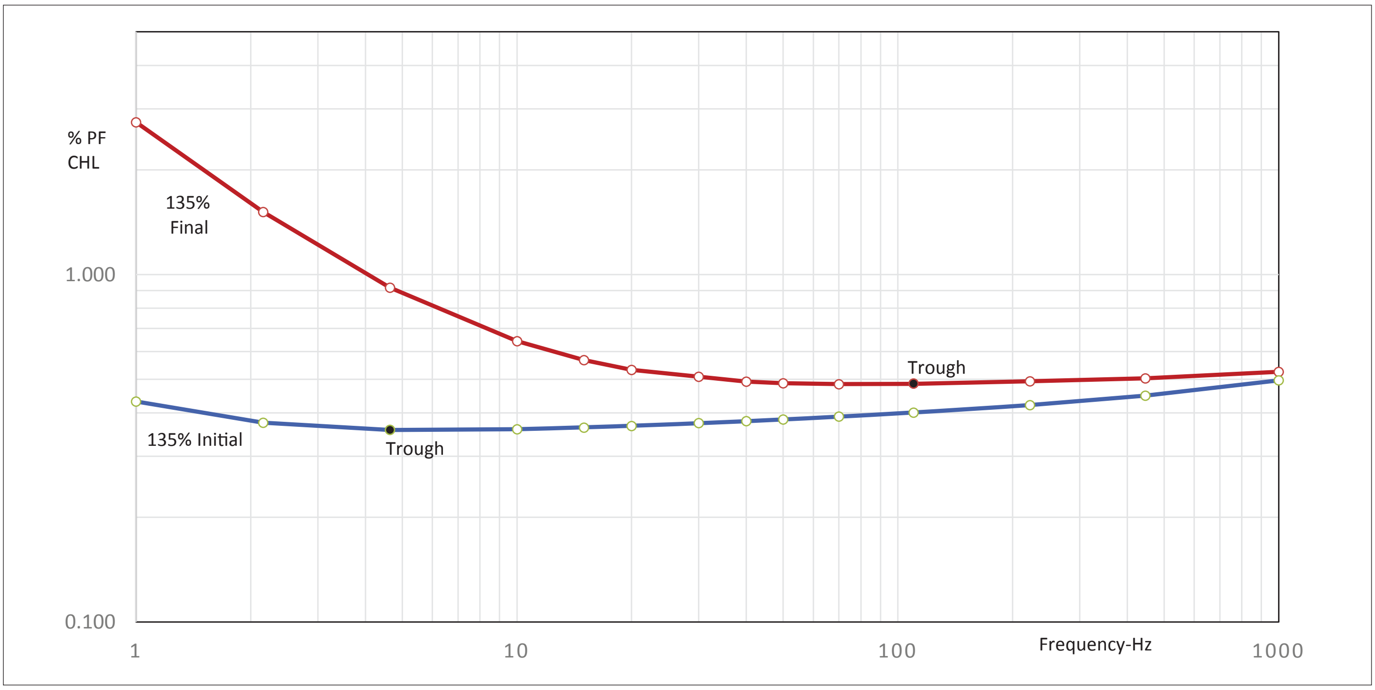



Figure 7. New vs degraded response

**In our studies, the acid number has proven to be the most consistent loading indicator of all of the oil quality tests**

correction factor (TCF) is further complicated when temperature gradients exist within the transformer.

The blue trace shown in Figure 7 represents the dielectric response from the initial condition of a unit loaded at 135 %. Because of negligible conductive losses, the response is dominated by the influence of static charge polarization losses [3]. In this condition, the response trace will be remarkably linear above and below 60 Hz. This linearity results in a relationship where the applied correction is proportional to the response movement driven by temperature variation. The slope at line frequency is positive for a transformer in good condition, therefore the applied correction shall be upwards as temperature increases.

Conversely, the dielectric response for the overloaded unit is shown as the red trace in Figure 7. Since this response is biased due to elevated watt losses, there is significant distortion of the trace, especially at the lower frequencies. This results in a relationship where the applied correction is not proportional to the response movement driven by temperature variation. Since the trough has migrated to 110 Hz, the slope at line frequency is negative. Therefore, as temperature increases and the response shifts to the right, the applied correction must be downward.

Conventional temperature correction tables are based on the assumption that the insulation system under evaluation is in good condition. It is therefore assumed that the slope at line frequency for the unit is positive, and that the applied correction will be reasonably proportional to response movement. However, in the case of the degraded response shown in Figure 7, both the magnitude and direction of correction will be incorrect. In order to further investigate this relationship, SCE performed an investigative study where the dielectric responses of three transformers with differing conditions were measured as the winding temperature was very slowly and incrementally increased over a period of weeks. The first specimen was a new unit with the trough located at 10 Hz. The second unit had been removed from service with the response trough located at 55 Hz. The final unit had been subjected to overload conditions and had a response trough located at 110 Hz.

As shown previously in Figure 7, the dielectric response of a unit in excellent condition is very linear from 10 to 1000 Hz. As illustrated in the inset of Figure 8, as temperature is increased from 18°C, the CHL at 60 Hz remains remarkably stable up past 45°C. This results in a linear TCF from 18 to 45°C. Eventually, as the response moves sufficiently for the trough to pass 60 Hz, the TCF begins to trend downwards.

As temperature is increased in specimen 55, the CHL initially decreases slightly. As the trough moves past 60 Hz, the CHL then begins to increase earlier and to a greater magnitude than seen in the new specimen. The TCF exhibits a hump from 18 to 30 Hz, which corresponds to the trough moving past 60 Hz. The TCF at higher temperatures for specimen 55 is greater than that for the new specimen due to the moderate distortion of the response at lower frequencies.

The CHL for specimen 110 rises immediately as temperature is increased due to the fact that the trough is well past 60 Hz. The magnitude of change for

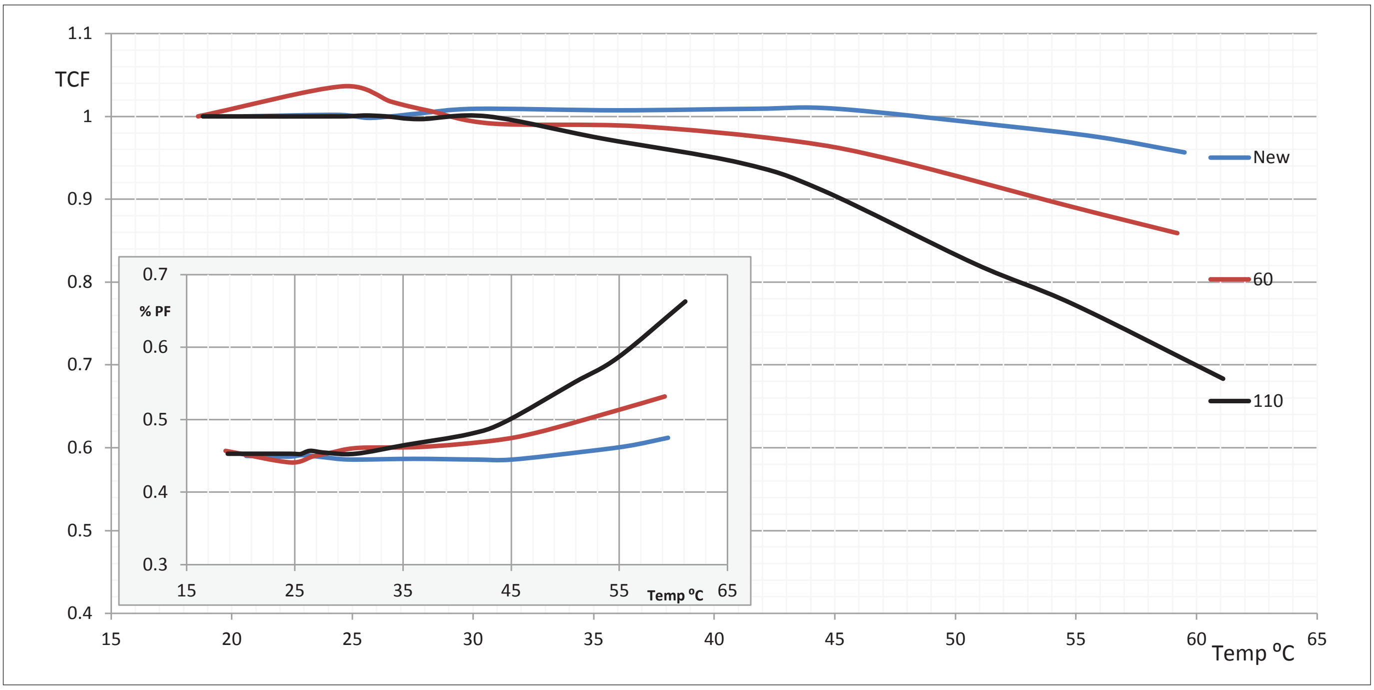


Figure 8. Temperature correction factor vs temperature (Inset CHL vs temperature)

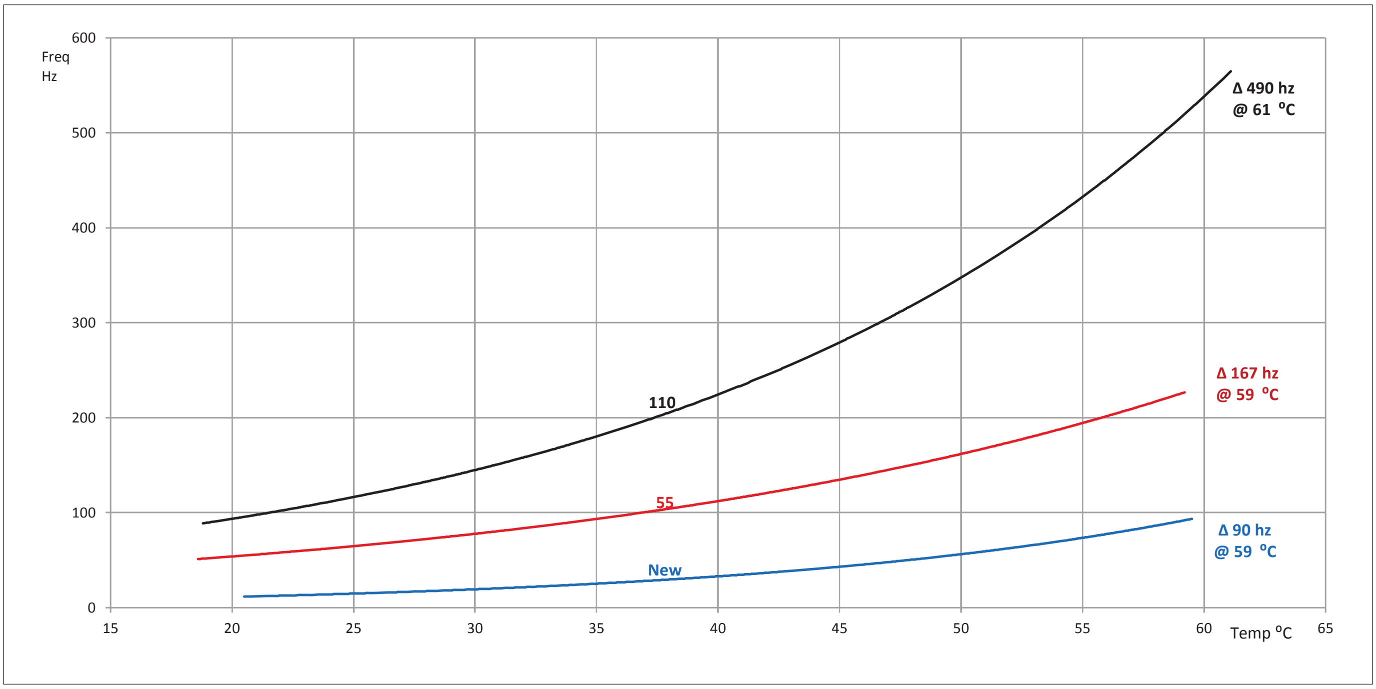


Figure 9. Trend lines for trough location (Hz) vs temperature °C

CHL is much greater than that generated by specimen 55 due to significant distortion of the dielectric response at lower frequencies.

The plots in Figure 9 demonstrate the changes in trough location for the three test specimens as temperature is increased. The magnitude of the trough migration is heavily influenced by the level of the conductive and polarization watts losses within the oil and paper. The location of the trough for the new specimen migrated 90 Hz upward as temperature is raised from 20°C to 59°C. Conversely, the trough for specimen 55 migrated 167 Hz, while the trough for specimen 110 migrated 490 Hz.

**Dividing the interfacial tension by the neutralization number provides a calculated parameter, the Oil Quality Index Number or Meyers Index Number, which is an excellent indicator of oil condition**

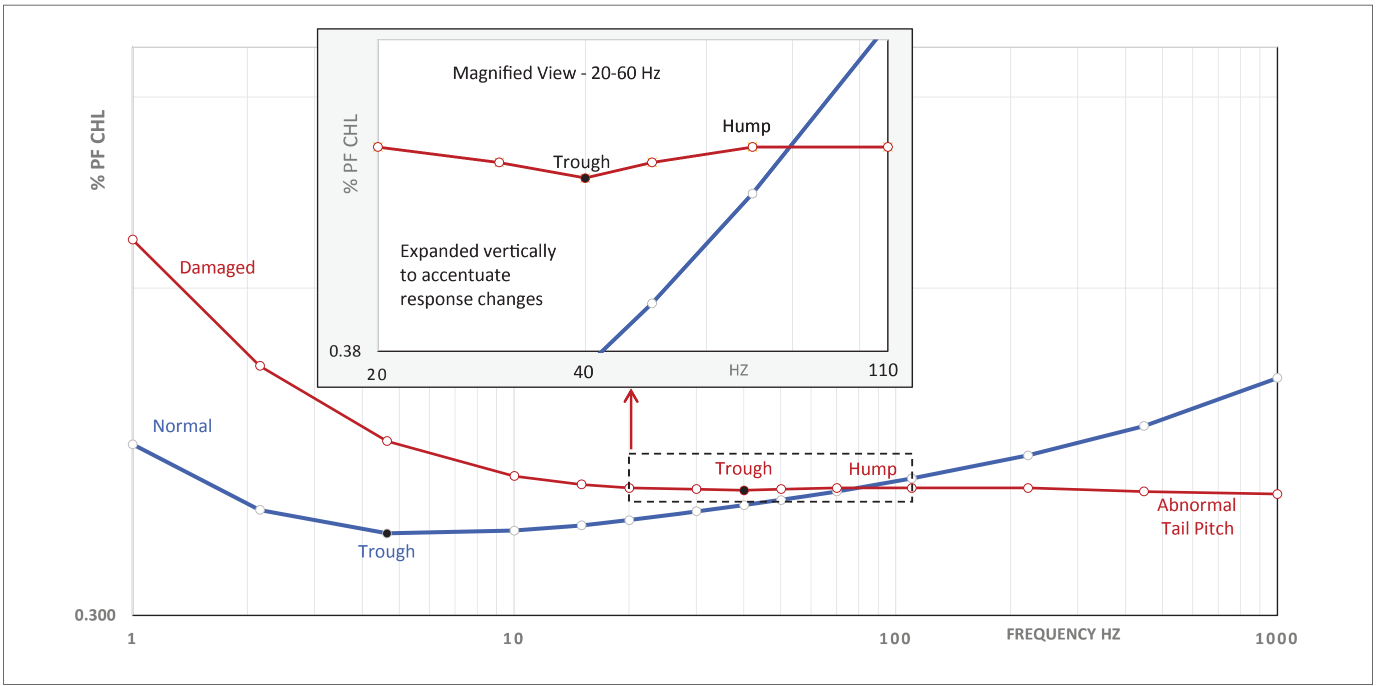



Figure 10. CHL response with high frequency dip

## 7. Abnormal response

Figure 10 illustrates an abnormal response seen in approximately 0.1 % of units returned from service for evaluation. It should be noted that this plot has been stretched along the Y axis in order to make the subtleties of the response visible. At first glance, the red trace would appear to be that of a degraded unit with the trough at 1000 Hz, but the magnitudes at 1 and 60 Hz would indicate that the unit is in excellent condition. A closer examination reveals that a trough exists at 30 Hz, and that the response above 70 Hz transitions into a negative slope. This creates the appearance of a subtle hump between 40 and 60 Hz. A very moderate capacitive current path in parallel with the CHL dielectric would account for this behaviour.

A unit with this condition was included in one of the studies, and was loaded at 90 % of rated load. After 1 month, the trough at 30 Hz disappeared, but the negatively sloped tail remained. At a later date, it was determined that this anomaly appears to be related to component damage and/or rough handling.

## Conclusions

SCE has found that CHL at 60 Hz is a very unreliable indicator of winding condition for some classes of distribution transformers. In these cases, the NBDFR trough location will supersede the 60 Hz magnitude as the primary assessment parameter. SCE is increasingly utilizing the magnitude at 1 Hz as a significant assessment tool, especially when trough location and 60 Hz magnitude are questionable.

In single phase loop feed transformers, the primary, secondary, and ground are common, therefore power factor and insulation resistance tests cannot be performed. In this scenario, the Oil Quality Index Number (OQIN) is an excellent indicator of general oil / winding condition.

A robust data base must be established in order to determine ideal responses for each of the transformer type in the utility inventory. A critical task for the operator is to determine normal vs abnormal responses for these units. Differing geometric influences are confronted when multiple manufacturers and voltage classes are evaluated, making interpretation ambiguous for the novice technician. This may be challenging when working with distribution class units where variation may be seen between similar units.

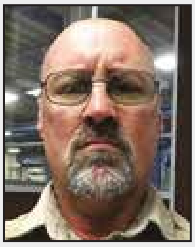
## References


[1] R.C. Breazeal, *Narrow Band Dielectric Frequency Response and Transformer Condition Assessment*, NETA, 2018, page 9

[2] R.C. Breazeal, D. Chhajer, *Expanding the Diagnostic Impact of Power Factor Testing*, Transformer Magazine, vol. 6, issue 2, p.p.112-116, April 2019.

[3] J. C. Duplessis, *Electrical Field Tests for the Life Management of Transformers*, Omicron electronics Corp USA, 2013, pp. 65


## Author




**Robert Breazeal** has 35 years of experience with the repair and testing of high voltage equipment with Southern California Edison. He currently provides technical oversight for transformer repair operations at the SCE Westminster Apparatus Repair Facility. Robert has published a number of papers and articles detailing research and diagnostic protocols developed at SCE.