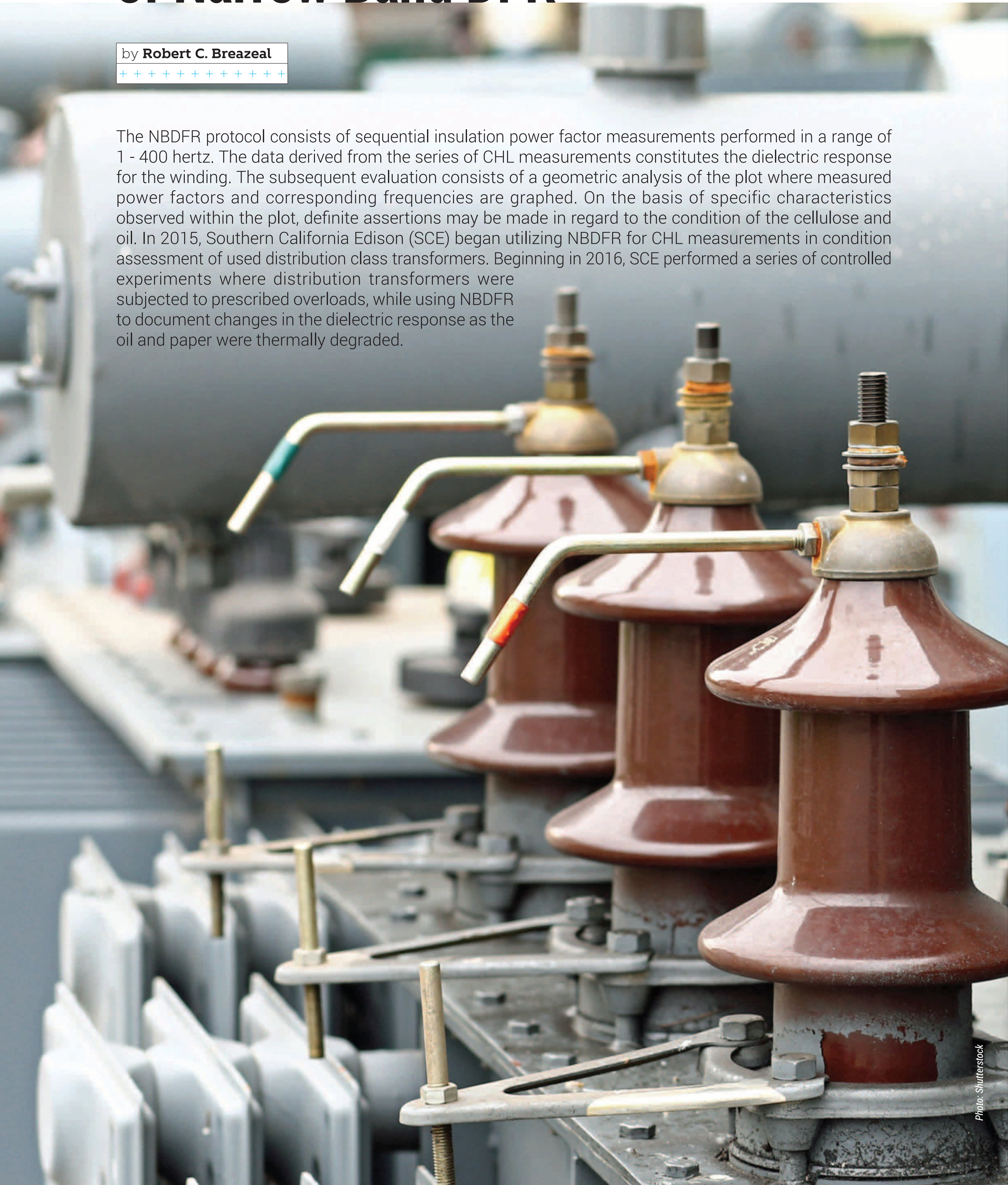
# Maximizing the Potential of Narrow Band DFR

by **Robert C. Breazeal**

The NBDFR protocol consists of sequential insulation power factor measurements performed in a range of 1 - 400 hertz. The data derived from the series of CHL measurements constitutes the dielectric response for the winding. The subsequent evaluation consists of a geometric analysis of the plot where measured power factors and corresponding frequencies are graphed. On the basis of specific characteristics observed within the plot, definite assertions may be made in regard to the condition of the cellulose and oil. In 2015, Southern California Edison (SCE) began utilizing NBDFR for CHL measurements in condition assessment of used distribution class transformers. Beginning in 2016, SCE performed a series of controlled experiments where distribution transformers were subjected to prescribed overloads, while using NBDFR to document changes in the dielectric response as the oil and paper were thermally degraded.



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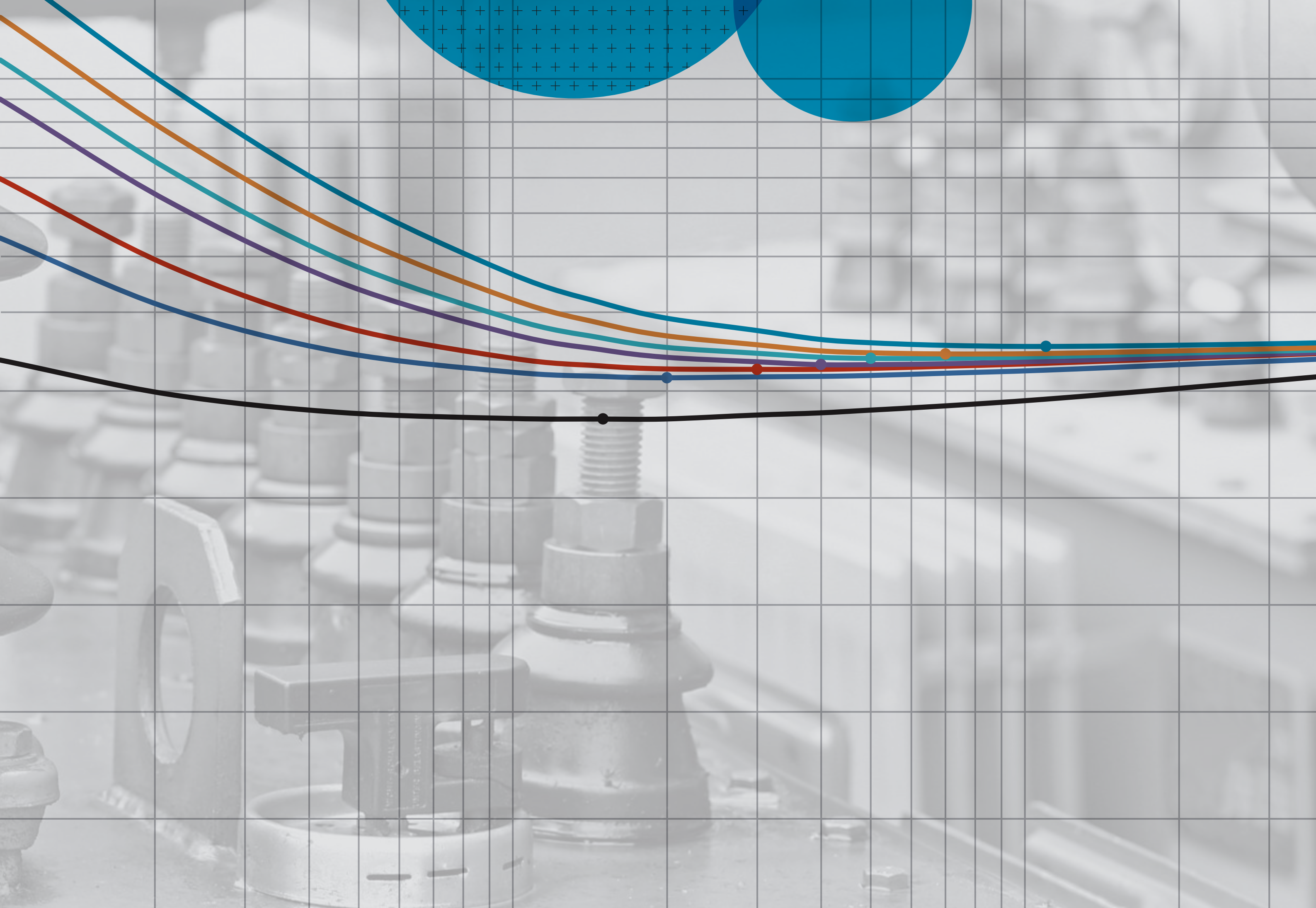
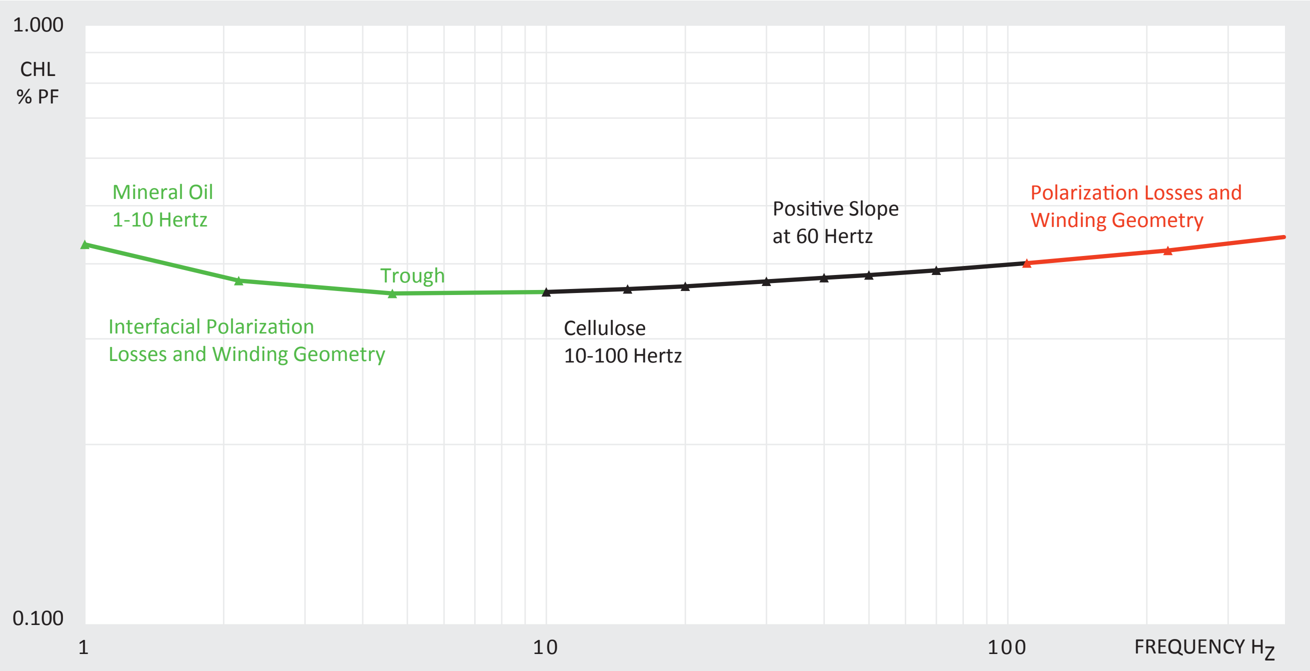


*Figure 1. Typical response for new distribution transformer*



## Components of the Narrow Band Response

A single measurement at line frequency (50 or 60 hertz) is the conventional method of insulation power testing. This method is problematic in that the capacitive current at line frequency dominates the measurement, with the conductive component comprising a very small percentage of the measured current. In this scenario when a moderate increase in conductive losses occurs within the insulation system, the change in power factor at line frequency may be barely detectible. However, as the applied frequency is decreased, the magnitude of the capacitive component decreases proportionally while the magnitude of the conductive losses remains constant. An increase in watt losses becomes increasingly visible as frequency decreases, making the NBDFR method tremendously sensitive to small changes in winding condition [1]. Because of this characteristic, NBDFR represents a quantum leap forward in winding condition assessment.

Figure 1 illustrates a typical NBDFR trace for a new distribution transformer. This response is driven by the individual influences of the mineral oil, cellulose insulation, and winding geometry. The effects of mineral oil dominate the response from 1-10 hertz as illustrated in the green portion of the response. In this illustration the point of minimum magnitude (trough) is shown to be at 10 hertz. This geometric feature is an important marker used for tracking changes in winding condition. Even minimal degradation of the dielectric fluid will result in a noticeable increase in magnitude at the low frequencies. This sensitivity is also driven in part by interfacial polarization as a result of winding geometry. Cellulose dominates the response from 10-100 hertz as illustrated in the black portion of the response. The response above 100 hertz is dominated by static charge polarization losses and the effects of winding geometry as illustrated in the red portion of the response.

## Response Interpretation

One prevailing viewpoint states that if the slope at line frequency is positive, the insulation system in question is in acceptable condition [2]. A deeper understanding of dielectric response however reveals that this is a significant oversimplification, in that the slope at line frequency is determined by the position of the trough [3]. The trough position in turn is driven by low frequency distortion of the trace which occurs as the insulation system degrades and watt losses increase. An increase in conductive and polarization losses has an exponential effect on the magnitude at 1 hertz.

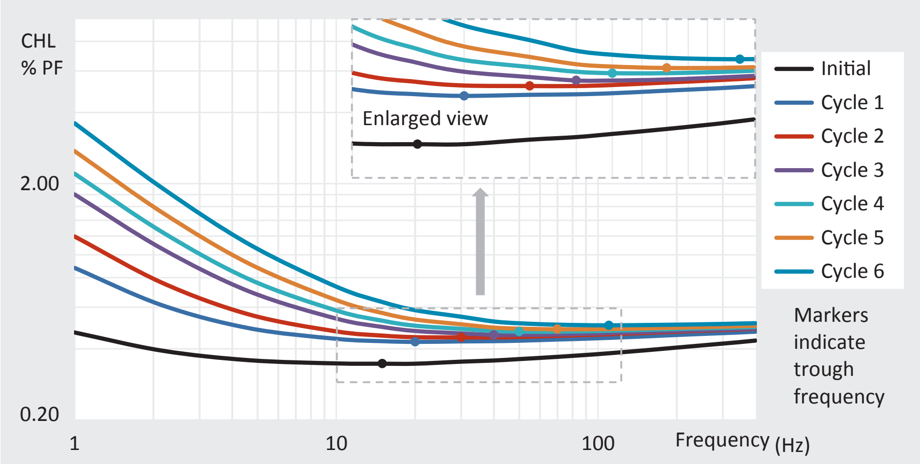
If the frequency at which the trough resides is monitored, this frequency may be used as a marker to track

changes in insulation condition which may not be reflected in the magnitude at line frequency [4]. In order to facilitate this method, extra test points can be inserted from 10-100 hertz. With smaller increments, subtle changes in trough position may be detected. If a robust data base is developed, condition classifications may be assigned for specific classes of transformers based on trough location [4].

## The Effects of Aging as Reflected by Dielectric Response

In 2015, SCE began using the NBDFR method for condition assessment of distribution class transformers, and it became immediately apparent that low frequency distortion and trough migration in many cases was not reflected in the magnitude at 60 hertz [5]. In order to gain an understanding of the aging process as reflected in the dielectric response, SCE performed an experimental protocol where 12 transformers were energized with loads ranging from 90 to 135% of nameplate rating. The units were de-energized on a monthly basis, and NBDFR measurements were performed at ambient temperature. Units which were loaded at 90% of nameplate rating showed minimal changes both in terms of magnitude at 60 hertz and frequency of trough location. Distortion at low frequencies was also minimal. However, Figure 2 illustrates the overlaid NBDFR results for a unit operated at 135% for six months. An analysis of the data reveals that the magnitude at 60 hertz increased from 0.366% to 0.510% resulting in a difference of 0.144%. Conversely, the magnitude at 1 hertz rose from 0.469% to 3.601% resulting in a difference of 3.132%. While difference of 0.144% for CHL at 60 hertz for a distribution transformer returned from service would be fairly normal, the increase illustrated at 1 hertz would be cause for grave concern. Also significant is the fact that the trough migrated all the way from an initial frequency of 15 hertz to 110 hertz after cycle 6. The preponderance of evidence in this case would indicate that this load would not be sustainable in the long term.

*Figure 2. NBDFR CHL responses for transformer loaded at 135% of nameplate rating [4]*



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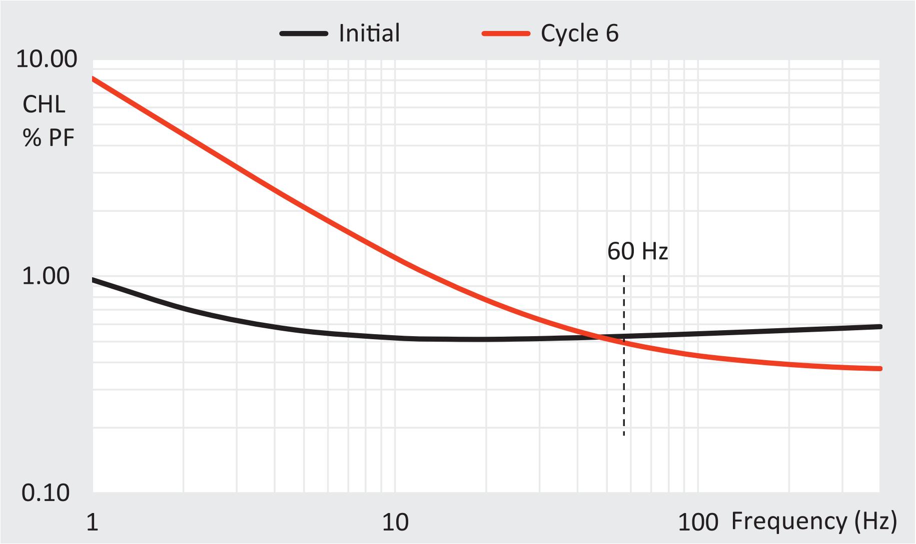
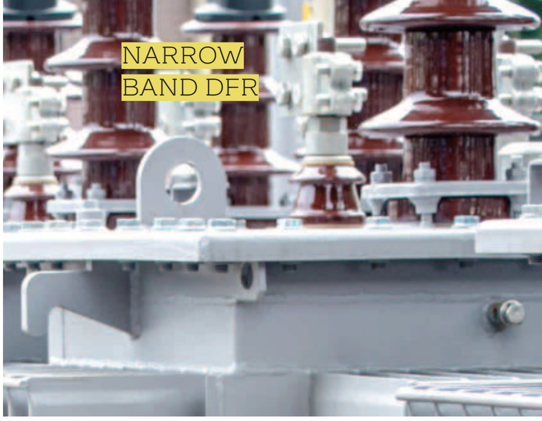
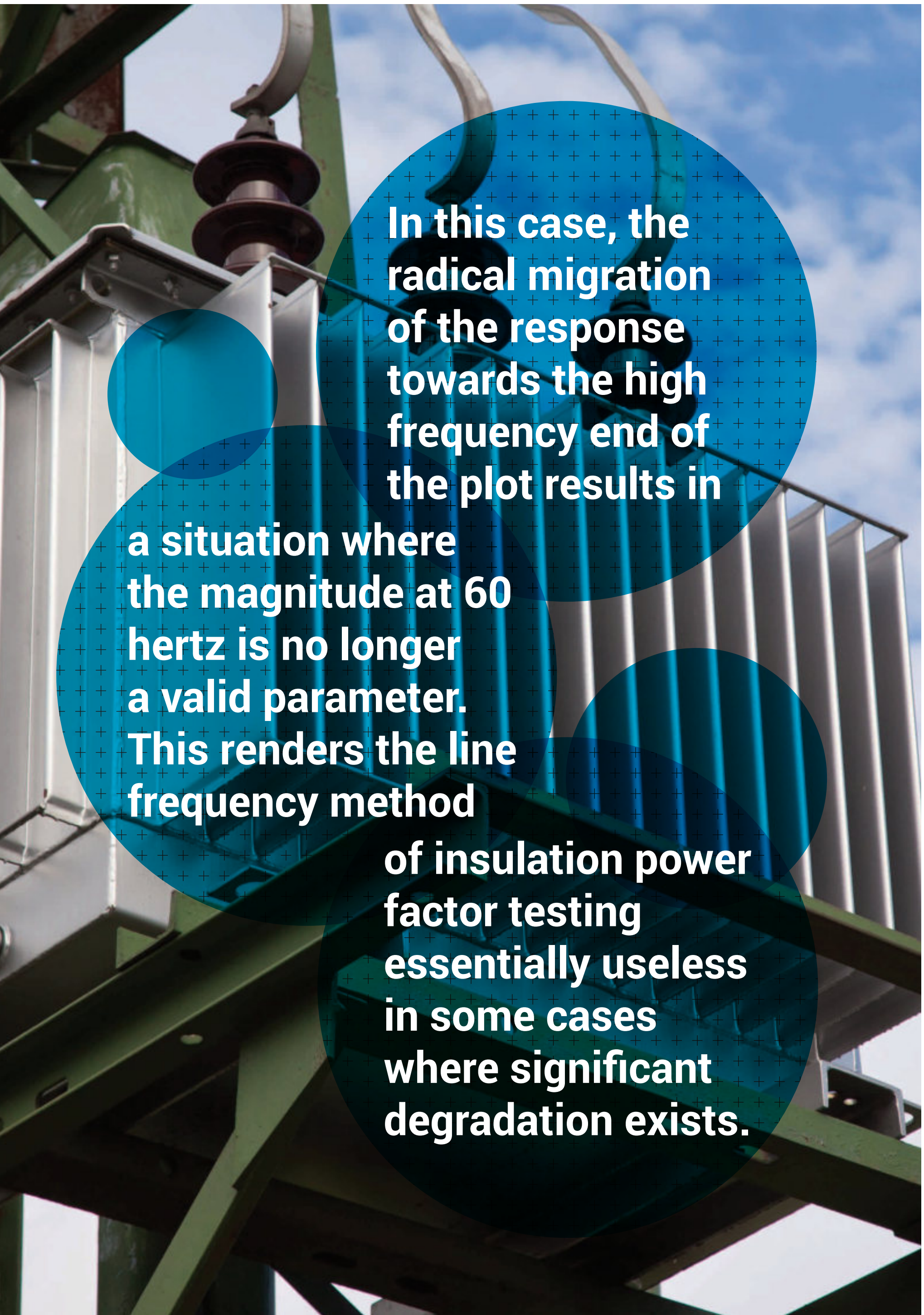
If the frequency at which the trough resides is monitored, this frequency may be used as a marker to track changes in insulation condition which may not be reflected in the magnitude at line frequency.

Figure 3. NBDFR CHL responses for transformer loaded at 150% of nameplate rating [4]





In a 2017 study, transformers were again subjected to overload in controlled conditions. Figure 3 illustrates the response traces for a unit operated at 150% of nameplate rating. The initial response is illustrated in black, with the month 6 response illustrated in red. After month 6 the magnitude at 1 hertz had risen to 8.14% which is clearly unsustainable. As would be expected, the trough migrated from an initial frequency of 20 hertz to a frequency of 446 hertz. The detail of overriding significance in this test case is the magnitude at 60 hertz after 6 months. With the highly elevated concentration of polar contaminants in the oil and cellulose, the assumption would logically be made that the magnitude at 60 hertz would reflect this situation. This, however, is not the case. **The magnitude at 60 hertz in this case actually decreased** from 0.530 % to 0.487%. In this case, the radical migration of the response towards the high frequency end of the plot results in a situation where the magnitude at 60 hertz is no longer a valid parameter. This renders the line frequency method of insulation power factor testing essentially useless in some cases where significant degradation exists.



In this case, the radical migration of the response towards the high frequency end of the plot results in a situation where the magnitude at 60 hertz is no longer a valid parameter. This renders the line frequency method of insulation power factor testing essentially useless in some cases where significant degradation exists.

## Bandwidths and Graphic Analysis

Some NBDFR test sets utilize a frequency bandwidth ranging from 15 to 400 hertz. In addition, some equipment software displays the response data using a linear plot. In Figure 4 the responses from the specimen loaded at 150% are depicted using the 15-400 hertz linear plot method.

When the linear plot is utilized in conjunction with the 15-400 hertz bandwidth, the vital data below 15 hertz seen in Figure 3 is absent. Because of the linear style plot, the responses are compressed

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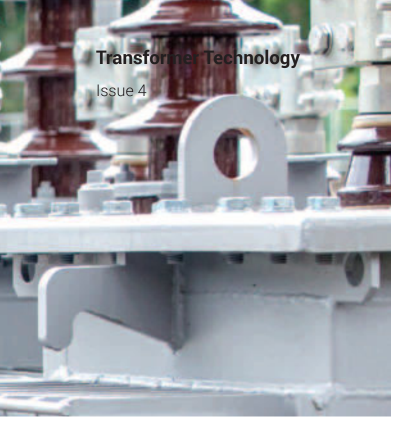


vertically; therefore, the trough frequencies in most cases cannot be determined without referencing the corresponding data table. In this case the response is sufficiently deteriorated to where it would still be identified as such, but in cases of mild degradation this bandwidth and format will prove to be problematic. The most obvious benefit of the logarithmic method is that the low frequency segment of the response is spread over a larger portion of the plot, making the critical information in the lower frequencies easier to extrapolate and analyze [6].

*Figure 4. Responses from unit loaded at 150% depicted using the 15-400 hertz linear plot*

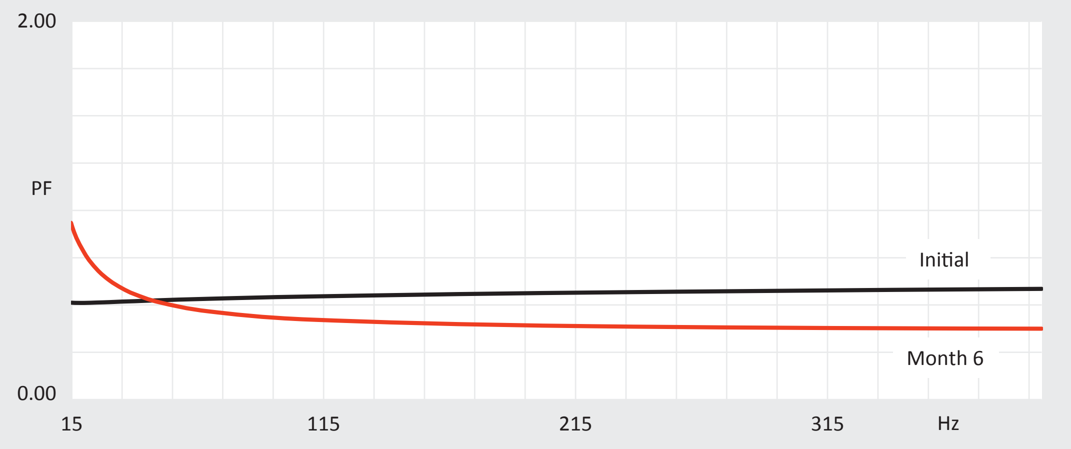
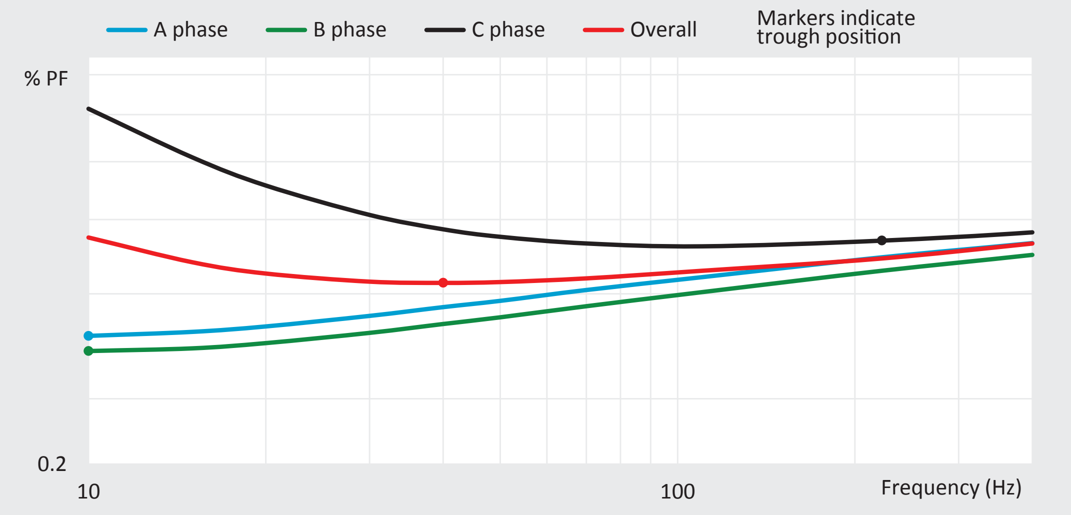


*Figure 5. Overall and per phase responses for 1 MVA D-Y transformer [4]*



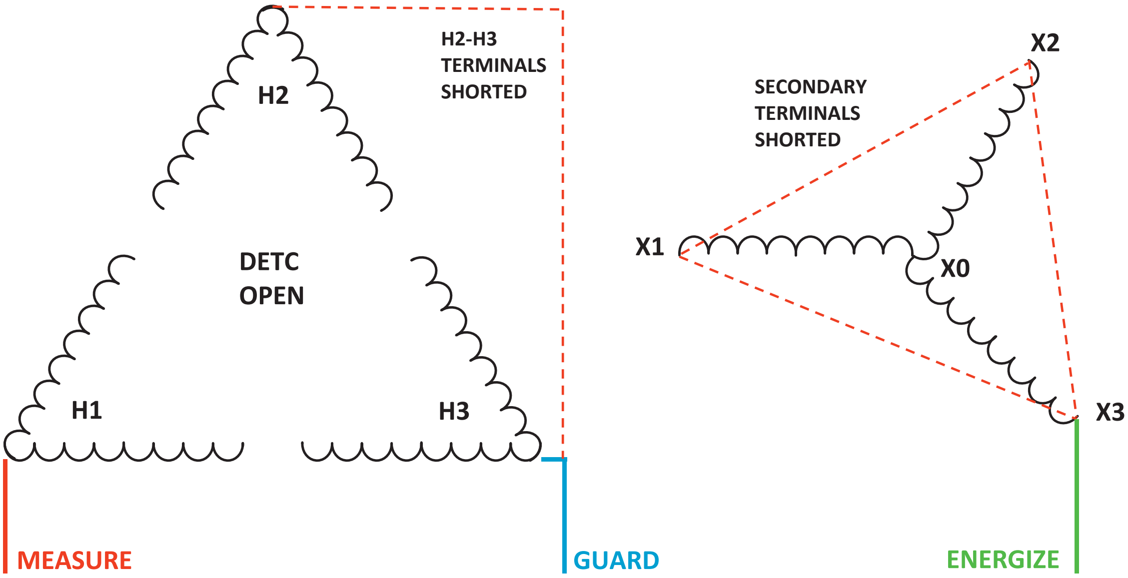
## Single Phase Evaluation of Three Phase Transformers

SCE has used the CHL NBDFR measurements for condition assessment of three phase distribution (<750 kVA) and medium power (750-3,750 kVA) transformers with tremendous success. It should be noted however, that when overall CHL power factor measurements are performed on a delta or wye winding, the measured response is the composite average for the three individual windings. Because of this, traditional winding tests cannot discriminate between uniform winding condition vs the presence of a significant localized problem. There are two methods which may be used to overcome this inadequacy. The first is to sectionalize the winding insulation. The second is to test the winding insulation over a wide range of frequencies [7]. SCE utilizes a technique which combines both of these methods, using the Delta-Wye Open Tap Changer Crosscheck Method in combination with a DFR test set. This allows the operator to extract CHL NBDFR responses on a per phase basis.

In 2015, an overall NBDFR CHL measurement was performed on a 2.5 MVA Delta-Wye configured transformer using a test set which generated potential over a bandwidth of 10-400 hertz. The magnitude at 60 hertz was within the normal range, with a trough frequency of 40 hertz as illustrated by the red trace in Figure 5. Although the 60 hertz magnitude and trough frequency are acceptable, there still existed the possible that an anomaly could exist in one or more windings. The open tap changer delta-wye crosscheck protocol was performed to extrapolate per phase NBDFR CHL responses. As illustrated in Figure 6, the tap selector is placed between taps and the secondary terminals are shorted. The guard lead is connected to the shorted H2 and H3 terminals, and the UST measuring lead is connected the H1 terminal. The secondary winding is energized at 500 volts and a UST measurement is performed to measure CHL [8]. As depicted in the diagram, CHL data is collected only from the winding interface common to the H1 terminal [5].

The A and B phase windings were in essentially new condition with both trough frequencies at 10 hertz, as seen in the green and blue traces. Conversely the C phase dielectric response differed significantly, with an elevated magnitude at 60 hertz and the trough frequency at 110 hertz, as seen in the black trace. Very serious elevation at 1 hertz is seen for C phase. This localized problem would have been absolutely undetectable using conventional insulation power factor testing methods.

*Figure 6. Test connections for open tap changer cross check method [8]*



## Conclusion

The NBDFR measurement in conjunction with a CHL measurement is the single most effective insulation quality test. However, in order to maximize the effectiveness of this analytical protocol, a robust data base must be established in order to establish normal magnitudes at 1 and 60 hertz, as well as normal trough frequencies for each transformer type in the utility inventory. Baseline responses for all new units should be recorded in order to facilitate the tracking of changes. When evaluating three phase transformers with a wye configured secondary winding, the crosscheck method should be utilized when the overall response differs from the previous test in order to verify that a localized problem is not developing.

The dielectric response will slowly migrate towards the high frequency end of the plot as temperature increases, so measurements should be taken as close to 20°C as possible. This effect is exacerbated in units which are degraded [9].

This localized problem would have been absolutely undetectable using conventional insulation power factor testing methods.

**References**

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