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Using Absolute Average Difference (DABS) in Interpreting the Frequency Response of Distribution Transformer

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Abstract. Different numerical indices have been proposed in different works to analyze the Frequency Response Analysis measurements, such as Standard Deviation, Spectrum Deviation, Absolute Sum of Logarithmic Error, and Correlation Coefficient. A comparative evaluation of absolute average difference (DABS) index on the same footing appears to have not yet been reported. In this paper, DABS is amongst the five numerical indices used in interpreting FRA that have been evaluated for their respective suitability, reliability and sensitivity based on the same test cases involving winding deformation of real life power transformers. It was found that DABS and ASLE are the most reliable and sensitive index for various transformer faulty conditions. On the other hand, CC is the least reliable index as it could not indicate faulty winding on most presented cases.

1. Introduction

Large power transformers are the most expensive and strategically important components of any power generation and transmission system [1]. On the other hand distribution transformer is an important electrical equipment of power supply system in the energy distribution system. With the electricity demand increased dramatically, more and more distribution transformers are being installed in the distribution system. Reasonable choice of distribution transformer capacity can not only effectively guides electricity sector to invest reasonably and economically, but also plays a key role in energy conservation and economic operation of distribution transformer. Transformer in electrical substation is a critical component because most distribution circuits are radial. Various factors have been the reason for transformer failure. According to the statistics showed in [2], 30% of total transformer failures are contributed from faulty winding.

To determine the condition of windings in transformer, frequency response analysis (FRA) test is commonly applied in the industry. FRA was initially proposed by E.P. Dick et al in [3]. The work was conducted on a 555 MVA, 230/22 kV, wye-delta generator step-up transformer. FRA is a comparative method where two measurements are compared to determine if disagreement has occurred between them. The disagreement indicates that the winding or core structure have been changed. To quantify the amount of dissimilarity, numerical or statistical indices can be used such as in [1]. However, every numerical index has its own performance. In [1], it was found that absolute sum of logarithmic error (ASLE) and standard deviation (STD) clearly distinguish the defective winding.

On the other hand, [4] proposed a new numerical index which is called absolute average difference (DABS). This reference however did not conducted any comparison on its performance with the previous ASLE. Based on the same works accomplished by the previous researchers, this paper presents an investigation on the suitability, reliability and sensitivity of the new DABS against the numerical indices as used in [1] and several others from different references.

2. Frequency Response Analysis

When a transformer is subjected to high through fault currents, the mechanical structure and the windings are subjected to large mechanical stresses [3][5]. These stresses acting on the windings creating differential forces could damage the windings and may lead to transformer failure. Sometimes displacements in the winding may result from:

- damages occurring during transportation of the transformers between the manufacturer and the installation location,
- short circuit forces imposed on the windings resulting from a low impedance fault occurring close to the transformer and
- natural effects of aging on the insulating structures used to support the windings.

Detection of these winding displacements in advance of a dielectric failure can reduce unplanned maintenance costs and provide the possibility to improve system reliability by preventing outages and breakdowns. FRA method is commonly used as a main diagnostic tool for identification of winding displacements in transformers by measuring their electrical transfer functions over a wide frequency range. Many electric utilities such as Tenaga Nasional Berhad (TNB) of Malaysia use the FRA as one of their diagnostic techniques to assess condition of power transformers [6].

Diagnosis of transformer winding displacements through FRA relies on correct interpretation of the measured results. FRA require trained experts to subjectively interpret the test results for making a judgment whether the variation between the two measurements (before and after) on the same winding is significant to suggest any problem on the transformer. This is quite similar to polarization and depolarization current (PDC) test where two or more sets of measurement are compared to estimate the moisture content and temperature of insulation in transformer [7]. However in FRA, currently there is no general guideline that has been developed for interpreting the frequency response. For this reason, utilities has to use their own approach or procedure to interpret the FRA. One of the approach to interpret the FRA is to use numerical or statistical indices. This is mentioned in the IEEE standard [8].

3. Analysing the Measured Response

3.1. Measurement Method

Omiron FRAnalyzer is a commercial equipment for measuring the frequency response of transformer. Figure 1 shows the connection of Omicron FRAnalyzer to a transformer on test. The device generate a sinusoidal voltage, V_{in} at a selected frequency (from 20 Hz to 20 MHz) and measure the output voltage, V_{out} amplitude and phase, on two input channels of “Reference” and “Measure”. Subsequently, the transfer function is determined from the ratio of output and input voltages, $20log_{10}(V_{out}/V_{in})$. The common way of representing the transfer function is based on Bode plot diagrams where both magnitude and phase response are illustrated. Two measurements (before and after fault) are required for comparison for assessing the transformer condition.

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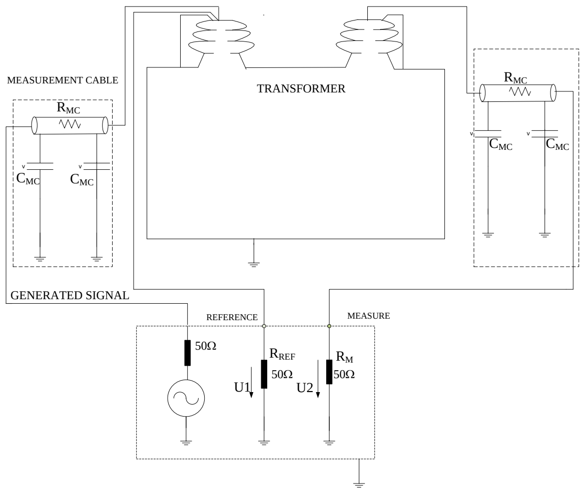


Figure 1. Connection of FRA test equipment on transformer.

3.2. Numerical Indices

As mentioned earlier that comparison using statistical indices is recognized in the IEEE standard [8]. Various numerical indices have been proposed in different works such as [4][9][10][11] to analyze the FRA measurements. Some of the indices available from the literature are Standard Deviation (STD) [1], Spectrum Deviation (SPD) [10], Absolute Sum of Logarithmic Error (ASLE) [9][12], Absolute Average Difference (DABS) [4] and Correlation Coefficient (CC) [13][12]. In this paper, these five numerical indices are evaluated for their respective suitability, reliability and sensitivity in analyzing three case studies taken from the utility. The equations of numerical indices used to analyze the FRA measurements are as follows:

$$STD_{xy} = \sqrt{\frac{\sum_{i=1}^{N}\left(x_i - y_i\right)^2}{N-1}} \quad (1)$$

$$SPD_{xy} = \frac{1}{N}\sum_{i-1}^{N}\sqrt{\left(\left[\frac{x_i-\left(x_i+y_i\right)/2}{\left(x_i+y_i\right)/2}\right]+\left[\frac{y_i-\left(x_i+y_i\right)/2}{\left(x_i+y_i\right)/2}\right]\right)} \quad (2)$$

$$ASLE_{xy} = \frac{\sum_{i=i}^{N}\left|20\log_{10} y_i - 20\log_{10} x_i\right|}{N} \quad (3)$$

$$DABS_{xy} = \frac{\sum_{i=1}^{N}\left|y_i - x_i\right|}{N} \quad (4)$$

$$CC_{xy} = \frac{\sum_{i=1}^{N} x_i y_i}{\sqrt{\sum_{i=1}^{N}\left(x_i\right)^2 \sum_{i=1}^{N}\left(y_i\right)^2}} \quad (5)$$

Where x_i and y_i are the i-th elements of the two measured responses respectively. N is the total number of samples in the frequency response. STD, SPD, ASLE, DABS and CC are designed to approach 0, 0, 0, 0 and 1 respectively if the shape of two set of data (two frequency responses) are identical. The best method is to compare FRA measurements with those obtained previously as a fingerprint or baseline. If reference fingerprints are not available, analysis can rely on comparison between two different phases of the same unit, twin or sister units of the same design [8]. The threshold values of the numerical indices for the FRA of a good mechanical condition in transformer core and winding can be summarized in Table 1.

Table 1. Threshold limits of the indices

Numerical Techniques	STD	SPD	ASLE	DABS	CC
Threshold limits for good condition	< 1.0	< 0.02	< 0.6	< 1.00	≥ 0.9970

4. Case Studies

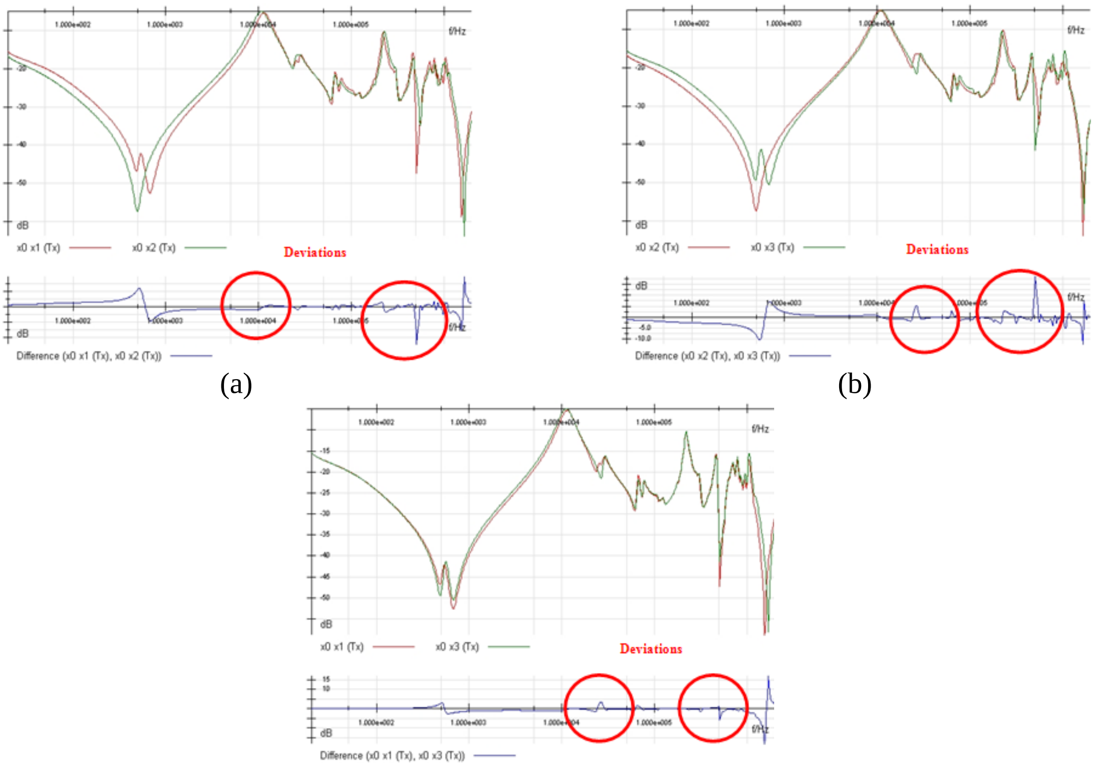
In this paper, three case studies which were taken from different transformers owned by a utility are presented. Each cases which has different faulty condition is used to evaluate the performance of each numerical indices (STD, SPD, CC, ASLE and DABS). The evaluation was made using three frequency bands which are low (1 kHz to 10 kHz), medium (10 kHz to 100 kHz) and high (100 kHz to 1MHz). Frequencies above 1 MHz are not considered since deviations on the response in this band are usually caused by poor grounding conditions, rather than any damage to the transformer [9].

The nature of mechanical faults that can possibly be detected using specific frequency bands are as follows [10][11]:

- Low band – core deformation, open circuits, shorted turns, residual magnetism and bulk winding movement relative to each other.
- Medium band – deformation within main and tap windings, hoop buckling failure, localized winding movement and winding asymmetry.
- High band – movement of main and tap winding leads and axial shift.

4.1. Case Study 1

In this case, a 7.5MVA, 33/11kV, three-phase, Dyn11 transformer is studied. Since no records of previous FRA measurements on the transformer were available, the comparison were conducted between phases of current measurements. The FRA measurements comparison between phases are shown in Figure 2 while the computed values of the five numerical indices are shown in Table 2.



(c)

Figure 2. Comparisons between LV windings. (a) u-n and v-n. (b) v-n and w-n. (c) u-n and w-n.

FRA results in Figure 2 show obvious deformation in the yellow (v-n) phase LV winding when compared with u-n and w-n windings. No or very slight deviation can be noticed in the response for u-n and w-n windings were compared in Figure 2(c) which indicating they are similar or no damage on the winding. Looking at Table 2, it shows that four of the numerical indices clearly indicating violation of the threshold limits for comparison with v-n phase except for CC. The bolded values in the table indicate violation of the threshold limits. When comparison is conducted between v-n and the other two phases indicates large deviation, this clearly suggest that the problem is on the v-n winding. STD however showed false indication in vn-wn comparison for medium frequency region.

Table 2. Numerical indices for LV winding FRA

Compared Phases	Frequency Band		Numerical Techniques				
			STD	SPD	ASLE	DABS	CC
un-vn	Low	(1kHz - 10kHz)	**1.9753**	**0.0246**	**0.8422**	**1.9283**	0.9997
	Medium	(10kHz - 100kHz)	0.7117	0.0160	0.3558	0.5437	0.9993
	High	(100kHz - 1MHz)	**3.6713**	**0.0224**	**0.6998**	**1.7954**	0.9980
vn-wn	Low	(1kHz - 10kHz)	0.9919	0.0169	0.3983	0.9224	0.9999
	Medium	(10kHz - 100kHz)	**1.2932**	0.0186	0.4831	0.8912	0.9980
	High	(100kHz - 1MHz)	**3.1716**	**0.0220**	**0.6765**	**1.7023**	**0.9909**
un-wn	Low	(1kHz - 10kHz)	0.7198	0.0126	0.4439	0.8159	0.9999
	Medium	(10kHz - 100kHz)	0.8705	0.0150	0.3123	0.5833	0.9990
	High	(100kHz - 1MHz)	0.8714	0.0110	0.1694	0.4794	0.9995

4.2. Case Study 2

A 15MVA, 33/11kV, three-phase, Dyn11 transformer is evaluated in this case study. FRA measurements on LV windings were compared with a sister transformer of the same design and in good condition due to the unavailability of reference fingerprint or baseline. The results of the FRA measurements comparison between LV phases are shown in Figure 3. All five calculated numerical indices are shown in Table 3.

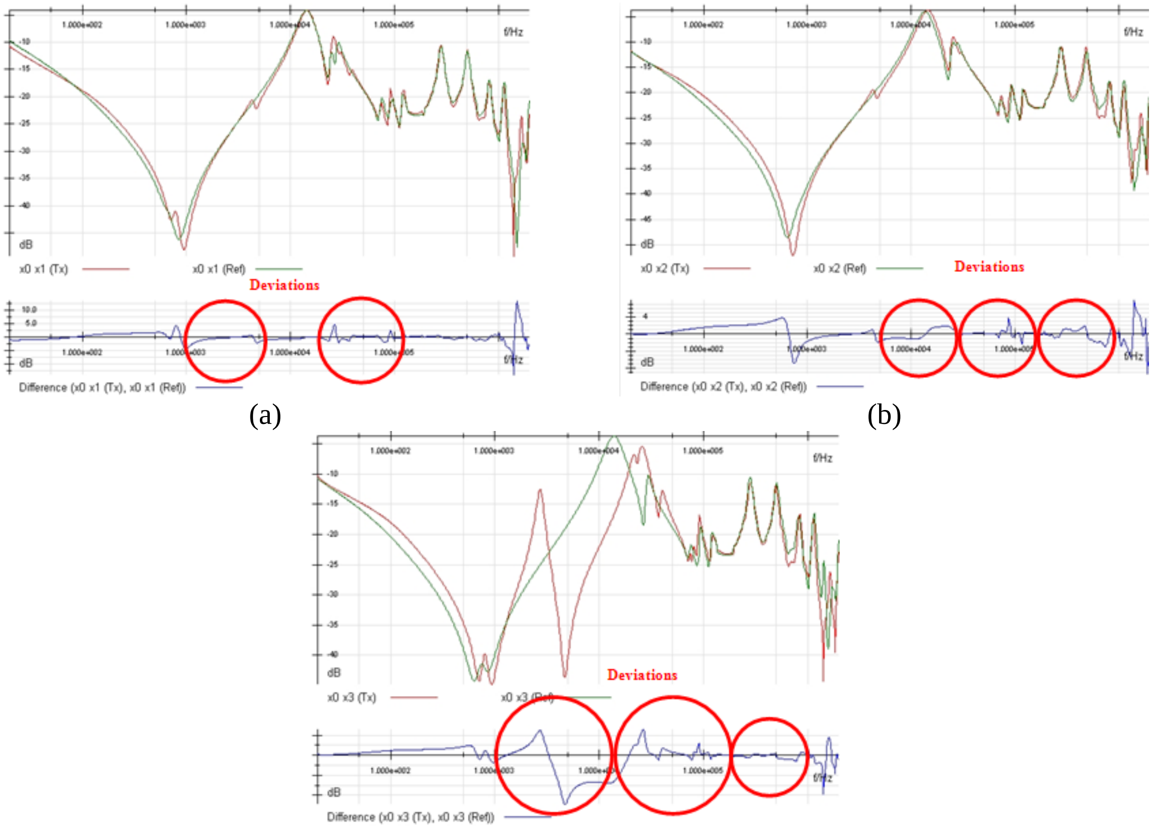


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Figure 3. Comparisons between phases. (a) u-n. (b) v-n. (c) w-n.

Table 3. Numerical indices for LV winding FRA

Compared Phases	Frequency Band		Numerical Techniques				
			STD	SPD	ASLE	DABS	CC
u-n	Low	(1kHz - 10kHz)	0.2228	0.0151	0.3164	0.8957	0.9995
	Medium	(10kHz - 100kHz)	0.0991	0.0189	0.4996	0.7471	0.9975
	High	(100kHz - 1MHz)	0.5630	0.0120	0.1995	0.4676	0.9996
v-n	Low	(1kHz - 10kHz)	0.8409	0.0150	0.3137	0.6933	0.9996
	Medium	(10kHz - 100kHz)	0.0746	**0.0226**	0.3118	0.8045	0.9979
	High	(100kHz - 1MHz)	0.1213	0.0168	0.3942	0.8668	0.9985
w-n	Low	(1kHz - 10kHz)	**11.4759**	**0.0496**	**3.5461**	**9.1946**	**0.9272**
	Medium	(10kHz - 100kHz)	**7.0245**	**0.0515**	**4.0273**	**5.0097**	**0.9049**
	High	(100kHz - 1MHz)	0.1239	0.0166	0.3845	0.8671	0.9986

It is observed that the response of blue phase (w-n) of LV winding deviates significantly especially in the low and medium frequency band. The remarkable differences reflected in frequency response comparison strongly indicate the possibilities that blue phase LV winding structure has been deformed. All five indicators showed violation of the threshold limits. This could suggest the damage on the winding is quite severe.

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4.3. Case Study 3

In this case study, a 15MVA, 33/11kV, three-phase, Dyn11 transformer is evaluated. Red phase winding (U-V) is known to have been deformed. Since no records of previous FRA measurement were available, measurements on a healthy sister transformer with same design have been used as a reference data and later compared with this faulty transformer. The results of the FRA measurements comparison between HV phases are shown in Figure 4. Results from numerical indices are shown in Table 4.

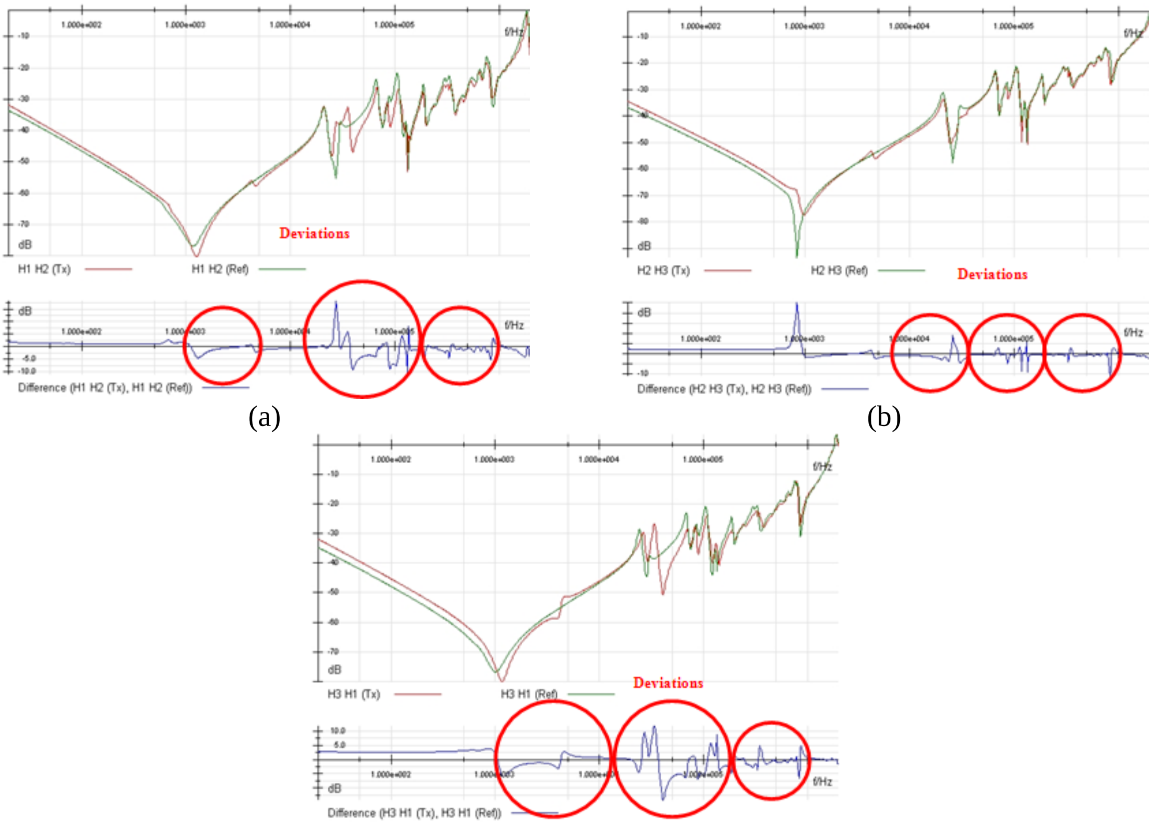

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Figure 4. Comparisons between phases (a) U-V (b) V-W (c) U-W

Table 4. Numerical indices for HV windings FRA

Compared Phases	Frequency Band		Numerical Techniques				
			STD	SPD	ASLE	DABS	CC
U-V	Low	(1kHz - 10kHz)	**1.5595**	0.0106	**0.5554**	**1.1597**	0.9998
	Medium	(10kHz - 100kHz)	**4.4746**	0.0119	**0.6679**	**2.8749**	0.9998
	High	(100kHz - 1MHz)	**2.4867**	0.0193	**0.5212**	**1.7359**	0.9996
V-W	Low	(1kHz - 10kHz)	0.0682	0.0099	0.1364	0.9121	0.9999
	Medium	(10kHz - 100kHz)	0.1276	0.0158	0.3469	0.5517	**0.0986**
	High	(100kHz - 1MHz)	0.1060	0.0164	0.3757	0.1507	**0.0972**
U-W	Low	(1kHz - 10kHz)	**2.3257**	0.0138	**0.6657**	**1.9126**	0.9995
	Medium	(10kHz - 100kHz)	**5.2863**	0.0161	**0.9487**	**3.8312**	**0.9906**
	High	(100kHz - 1MHz)	**2.5392**	**0.0214**	**0.6346**	**1.9351**	**0.9955**

From the FRA results, it can be seen that the frequency response involving U-V and U-W windings of the delta side showed obvious deviation. In this case, STD, ASLE and DABS consistently agreed for all three frequency bands. Results from SPD and CC on the other hand shown uncertainty. Almost all numerical indices clearly detected red phase HV winding deformation.

The summary for the performance of all numerical indices are presented in Table 5. ‘ok’ indicates that the index violates the threshold limit thus imply that the winding has been damaged. On the other hand, ‘x’ indicates incorrect analysis where the index did not suggest that the winding is faulty. Out of these five indices, STD, ASLE and DABS clearly shown that they can discriminate all defective windings. However as presented in the first case study, STD showed a minor false indication. CC on the other hand is the least reliable index according to this study.

Table 5. Numerical indices performance

Case Study	1	2	3
Condition	Winding fault: yellow phase LV	Winding fault: blue phase LV	Winding fault: red phase HV
Comparison Method	Between phases	Sister transformer	Sister transformer
STD	ok	ok	ok
SPD	ok	ok	x
ASLE	ok	ok	ok
DABS	ok	ok	ok
CC	x	ok	x

5. Conclusion

In this work, the performance of the numerical indices have been evaluated for analyzing the frequency responses of transformers for detecting winding deformation or displacement. All presented case studies were taken from actual power transformers owned by a local power utility. DABS is the main interest in this paper to determine its performance compared with other indices. It has been observed that DABS is as reliable and sensitive as the ASLE. Therefore this paper recommend to use both indices together in future analysis and interpretation to provide more objective and confident comparison of FRA results. Possible future work is to include wider range of transformer designs and types to evaluate the performance of these indicators.

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