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Objective Interpretation of SFRA, in the Light of CIGRE TB 812

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Abstract

The SFRA (Sweep Frequency Response Analysis) technique has become quite popular as a condition monitoring technique for transformers. The SFRA technique holds a vast repertoire of data in terms of the electromagnetic behaviour of the transformer. Much research has happened in comprehending this data but no effort has succeeded in determining a universal objective criterion for the interpretation of SFRA data. CIGRE study committee A2.53 has recently released Technical Brochure 812 which has been the result of nearly half a decade of international efforts in arriving at an objective criterion for the interpretation of SFRA. This paper discusses the state of the art in objective interpretation of SFRA data with special reference to TB 812. The paper also presents a case study in HPL where SFRA was compared to a conventional method.

Keywords: Frequency Response, Power Transformers, Statistical Analysis

1. Introduction

Transformers constitute a very important power system asset whose failure can result in total disruption of supply. The high cost of failure has prompted the development of a plethora of condition assessment techniques targeted at accurate determination of mechanical and dielectric health of the transformer. SFRA has evolved much since its first theoretical emergence in the late seventies. SFRA has almost edged out the low voltage impulse techniques as the main transfer function analysis technique of transformers. The transfer function of the transformer is fairly complex in line with its complex electromagnetic structure.

$$\text{T.F.} = H(\omega) = \frac{V_{out}}{V_{in}} \quad (1)$$

An analytical derivation of the transfer function is beyond our present understanding. A computational solution of the Maxwell's equations will yield the transfer function but physical understanding will elude us. SFRA gives the transfer function observationally but this comes with an absolute lack of insight of the associated phenomena. Hence deriving useful information is proving to be a tough challenge. The common technique used for interpreting SFRA data is by comparing the traces before and after an event. Even this method has proven to be a vexing challenge since there is no direct correlation between changes in the traces and physical changes in the transformer.

Several attempts have been made to standardize the measurements and interpretation. The measurement techniques has been standardized more or less ever since. The global practice is to use a low voltage sinusoidal signal sweep as the input and directly measure the output to derive the transfer function rather than opting for driving point impedance measurements. The frequency range of measurements has been accepted to be between 20Hz and 2 MHz. A typical SFRA trace is shown in Figure 1.

2. Efforts at Standardisation

2.1 CIGRE TB 342

CIGRE working group A2.26 was constituted in the year 2003 to explore the possibility of standardising the measurement and interpretation of SFRA. As a result

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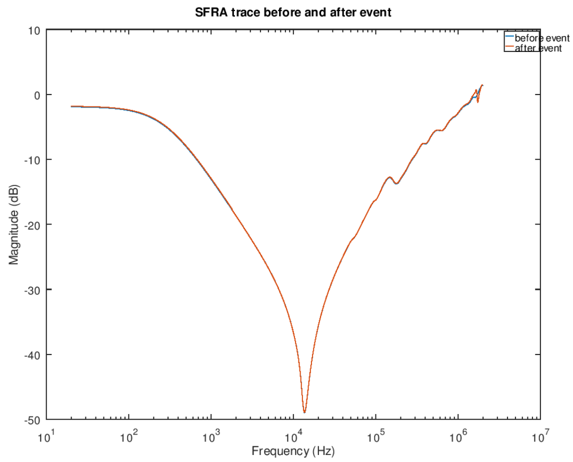

Figure 1. A typical SFRA trace.

the technical brochure 342 has been published in the year 2008. The main contribution of TB 342 has been the establishment of four measurement configurations[1].

(i) End to end open circuit measurement
(ii) End to end short circuit measurement
(iii) Inductive inter-winding measurement
(iv) Capacitive inter-winding measurement

The technical brochure also established the requirements for the test device and measurement techniques. The technical brochure also has a section on the interpretation of SFRA. TB 342 recognises visual inspection as the main existing criterion for interpretation of SFRA and recommends the double logarithmic scale for general evaluation. It is suggested that there are two methods of comparison

(i) Signatures of the same unit at different times
(ii) Comparison with traces of sister units

The technical brochure introduces the use of statistical parameters for interpretation of SFRA. It is recommended to use electromagnetic simulation, not for direct comparison, but for estimating the expected differences due to known defects. The method of comparison by utilising pole-zero representation of the transfer function is also presented. Techniques based on artificial intelligence are also presented. It was hinted that the possibility of evaluation without comparison with a reference trace needs to be evaluated.

2.2 IEC 60076-18

IEC standard[2] was published in 2012 and was formulated building on the foundations of CIGRE technical brochure. The standard focused on measurement configurations, device requirements and best practices. Examples were presented with known failures and SFRA deviations. However no solid recommendation for interpretation was presented.

2.3 IEEE C57.149

The IEEE standard[3] was also published in 2012 borrowing heavily from CIGRE technical brochure. Measurement configurations were suggested for different vector groups. Regarding interpretation, examples were presented and frequency ranges of interest were suggested. For example, it was stated that radial deformation manifests in considerably higher frequency range compared to axial deformation.

2.4 Chinese Standard DL/T911

The Chinese standard[4] was the first to propose an objective criterion for the evaluation of SFRA results. The evaluation was based on a statistical parameter known as Relative Factor (Rxy). The relative factor was defined in three frequency regions – (a) Low Frequency – 1 – 100 kHz, (b) Medium Frequency – 100 – 600 kHz, (c) High Frequency – 600 – 1000 kHz. The criteria is elaborated in Table 1.

2.5 CIGRE Technical Brochure 812

CIGRE working group A2.53 was constituted in 2016 to work out objective interpretation strategies for SFRA data. The findings of the group were published in technical brochure 812[5]. The technical brochure detailed the understanding of SFRA data from circuit modelling and comprehending the prominent electromagnetic phenomena at different frequency ranges. Factors

Table 1. Evaluation criteria in dl/t911

Winding deformation	Threshold values
Severe	$R_{LF} < 0.6$
Obvious	$(1.0 > R_{LF} \geq 0.6)$ or $(R_{MF} < 0.6)$
Slight	$(2.0 > R_{LF} \geq 1.0)$ or $(0.6 \leq R_{MF} < 1.0)$
Normal	$(R_{LF} \geq 2.0)$, $(R_{MF} \geq 1.0)$ and $(R_{HF} \geq 0.6)$

influencing measurement are elaborated upon and several case studies are presented. Quantitative SFRA interpretation strategies are explained in detail with theoretical and practical comparison with case studies. The strategies are explained in the next section.

3. Quantitative Interpretation Strategies in TB 812

3.1 Based on Numerical Indices

Numerical indices are statistical parameters which are derived from SFRA data. They give a single numerical value which gives the extent of variation of the two SFRA traces being compared. They are usually calculated in the entire frequency range but sometimes they are calculated in specific ranges and collated to derive any meaningful inference. The most prolific research in SFRA interpretation has been carried out in this area only[6]. This section is a summary of the study carried out in[5]. They are divided into four categories:

(i) Based on frequency response traces

These are indices which are calculated by treating the entire frequency response trace as statistical data. Mostly they are calculated using amplitude data in dB, though there are a few indices which utilise phase data as well.

(ii) Based on resonance frequencies

The SFRA trace will contain crests and troughs which are known as resonant and anti-resonant points. These are very important data points since they are reflective of the natural frequencies of the transformer. Any change in the natural frequencies will reflect a change in the electromagnetic structure of the transformer. Hence there are numerical indices based on the changes in the resonant and anti-resonant points. However, the identification of these points will be challenging as the presence of noise dislocates them.

(iii) Based on vector fitting

This approach fits a rational function to the SFRA data and utilises the changes in the poles and coefficients to measure the deviation between the traces. However there are many difficulties in this approach since the rational function is not unique. The degree of the polynomial as well as the pole positions are all variable and hence different techniques yield different values for the indices.

(iv) Based on vector based sliding window[5, 7]

This approach is relatively new and uses a sliding window that traverses along the trace and calculates a numerical index for each instance and then calculates another index which gives the minimum of the deviation along the trace. This approach has shown promising results even though the studies on it are not many.

3.2 Based on white box models

These methods are based on the theoretical modelling of the transformer. There are two types of models usually employed:

(i) RLC Network

The transformer can be modelled as a ladder network of R, L, C elements. A sample ladder network is shown in Figure 2. The elements can be estimated using geometric parameters of the transformer. Otherwise it is possible to arrive at the values from terminal measurements carried out on transformers using optimisation methods. The effect of faults on parameter values and the effect of changes in parameter values on frequency response needs to be known from an established database. The method is simplistic compared to full computational modelling while holding great potential for identification and localisation of fault. It has the advantage of requiring only FRA measurements for deriving all the parameters. The circuit modelling method suffers from conceptual shortcomings in the high frequency domain.

(ii) FEM Modelling

FEM modelling involves the geometrical modelling, high frequency computational modelling and sinusoidal excitation of the model. This method does not involve circuit synthesis and directly solves a version of the Maxwell's equations and hence is capable of estimating all phenomena. The effects of all faults on frequency response can be easily studied and is most accurate at high frequencies. But this method is predominantly used in academia.

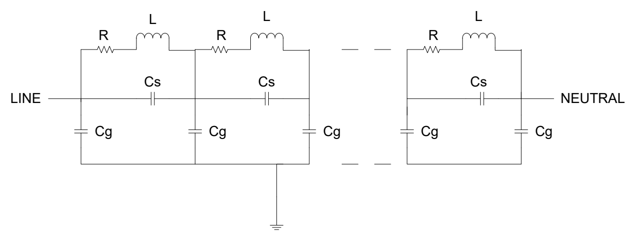

Figure 2. RLC model network.

(iii) Based on Artificial Intelligence

Artificial intelligence techniques are used in circuit synthesis or directly in fault identification. The most common methods used are decision trees and neural networks. Decision trees branch out to various possibilities depending on the values of parameters. Neural networks use many inputs and process the data through many layers to arrive at binary values for known outputs. The method requires a large database for training which may not be available in the field. Standardisation has a long journey with these methods.

3.3 Evaluation Of Numerical Indices

The numerical indices were evaluated on four parameters[5]:

(i) Monotonicity

This is the property by which the index increases or decreases without reversal with monotonically increasing extent of fault. This property is mandatory if meaningful quantifying data is to be derived from frequency response traces.

(ii) Linearity

This is the property by which the index increases by the same amount with same increase in extent of fault. This is also very important for quantification of the extent of fault. The indices which are using powers more than two in calculation cannot be expected to be linear.

(iii) Sensitivity

This is the property by which the index shows sufficient response to frequency and amplitude changes (horizontal and vertical shifts). A good index should be sufficiently sensitive to frequency and amplitude changes.

(iv) Dependence on data points

A good index should not be sensitive to reasonable changes in the number of data points. IEC standard requires a minimum of 200 data points per decade.

Based on the above properties, the following indices were selected for evaluation with case studies:

(i) Standardised Difference Area

$$\frac{\int |Y(f) - X(f)| df}{\int |X(f)| df} \quad (2)$$

(ii) Root Mean Squared Error

$$\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{(|Y(i)|-|X(i)|)}{\frac{1}{N}\sum_{i=1}^{N}|X(i)|}\right)^2} \quad (3)$$

(iii) Sum of Error

$$\frac{\sum_{i=1}^{N}(Y(i) - X(i))}{N} \quad (4)$$

(iv) Sum of Squared Error

$$\frac{\sum_{i=1}^{N}(Y(i) - X(i))^2}{N} \quad (5)$$

(v) Sum of Squared Ratio Error

$$\frac{\sum_{i=1}^{N}\left(\frac{Y(i)}{X(i)} - 1\right)^2}{N} \quad (6)$$

(vi) 1-CCF (Cross-Correlation Factor)

$$1 - \frac{\sum_{i=1}^{N} Y(i).X(i)}{\sqrt{\sum_{i=1}^{N}[X(i)]^2 \sum_{i=1}^{N}[Y(i)]^2}} \quad (7)$$

(vii) 1-LCC (Lin's Concordance Co-efficient)

$$1 - \frac{2S_{XY}}{(\overline{Y} - \overline{X})^2 + S_X^2 + S_Y^2} \quad (8)$$

The above indices were evaluated in three frequency sub-bands – 1-10 kHz, 10-500 kHz and 500 kHz – 1 MHz in[5]. Six case studies with various deformations were considered. The indices were calculated for a normal case and deformed case and the ratio was taken as index ratio.

In the case studies, 1-CCF, 1-LCC, SSE and SSRE showed the best sensitivity overall. However the technical brochure recommends that the frequency sub-bands need to be fixed along with the number of measurement points in a decade.

The calculation of winding assessment factor (SDD (i)) being used in vector based sliding window approach is shown below[5,7]:

$$\overline{SDD(i)} = -2\left(\sqrt{\frac{\sum_{j=1}^{ws}\left(Z(j)-\overline{Zw(i)}\right)^{\wedge 2}}{ws-1}}\right) \quad (9)$$

The calculation of the individual terms is not elaborated here but is detailed in[5,7].

TB 812 accepts that there is no single index which can act as a sole criterion of interpretation. The prediction is that a set of numerical indices can be fed to a machine learning algorithm which can then decide on the presence of a fault.

4. HPL Experience

High Power Laboratory at CPRI, Bangalore has been conducting short circuit tests on power and distribution transformers for almost three decades. The short circuit tests provide a unique opportunity to assess the capability of SFRA as a diagnostic tool for various kinds of transformer damage. As a preliminary step, attempts were made to identify linear correlation between SFRA numerical indices and short circuit reactance measurements of transformers which is currently the gold standard for identifying winding deformations in transformer. No significant correlation could be found in the studied sample[8].

4.1 Case Study

A case study of a 35 MVA, 23.5/11.5 kV three phase power transformer which was short circuit tested at HPL is presented here. The transformer suffered winding collapse in the V phase with associated minor deformation in the extreme phases. The variation was evident in the short circuit reactance measurements. The phase wise reactance changes are shown in Table 2. Since SFRA measurements are carried out phase to phase, reactance variations are also considered phase to phase[8]. SFRA measurements were carried out FRAX 101 equipment with a frequency range of 20 Hz to 2 MHz with a frequency resolution of 200 per decade as per[2]. The calculations were carried out using magnitude values only. The calculated SFRA indices with open configuration of LV windings and reactance measurements are shown in Table 3.

The trend shown in Table 3 is not as expected. Both reactance measurements and SFRA data show significant damage. The collapsed winding appears mainly between U and V terminals. But SFRA indices show greater damage between V and W while reactance measurements show greater damage between U and V. Table 3 shows the SFRA indices with LV windings shorted which is the measurement configuration for short circuit reactance as well.

Table 4 also shows the same trend as in Table 3. The sliding window approach is also explored for the same case. The minimum value of the winding assessment factor in each configuration is presented in Table 5.

The plot of SDD (i) against frequency for VW-LV open measurement is shown in Figure 3.

This actually reflects on the complexity of SFRA where not only winding deformation but also changes in series and parallel capacitances affect the measurements. This case study cements the conclusion already reached by the authors in[8]. A straightforward replacement of short circuit reactance measurements by available SFRA indices seems to be infeasible. SFRA, being a complex repertoire of data

Table 2. Reactance variation

Phases	Reactance change (%)	Corresponding Phase	Reactance change in Phase (%)
UV	7.00	V	10.6
UW	2.16	U	0.66
VW	2.25	W	0.52

Table 3. SFRA indices with lv open

Phases	Reactance change (%)	1-CCF	1-LCC	SSRE	RMSE
UV	7.00	0.07	0.08	0.03	0.14
UW	2.16	0.14	0.17	0.03	0.22
VW	2.25	0.31	0.33	0.12	0.28

Table 4. SFRA indices with LV shorted

Phases	Reactance change (%)	1-CCF	1-LCC	SSRE	RMSE
UV	7.00	0.03	0.03	0.05	0.13
UW	2.16	0.04	0.05	0.02	0.15
VW	2.25	0.19	0.19	0.24	0.30

Table 5. Winding assessment factor

Phases	Reactance change (%)	Minimum Value of SDD	
		LV Open	LV Shorted
UV	7.00	-11.6	-8.7
UW	2.16	-21.3	-16.5
VW	2.25	-22.4	-22.5

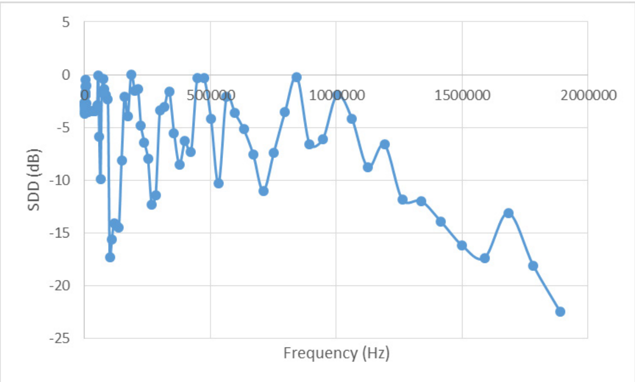

Figure 3. Plot of SDD (i) versus Frequency.

regarding all components of the transformer, calls forth sophisticated methods for its accurate interpretation.

5. Conclusion

This paper summarises the journey of standardisation of SFRA measurement and interpretation. CIGRE technical brochure 812 builds on its previous incarnation of 342 and represents the gist of one decade of advancement and more than half a decade of concerted international effort. The technical brochure emphasises numerical indices coupled with artificial intelligence algorithms as the future of SFRA interpretation. However TB 812 recognises the lacunae to be addressed before a universal concrete criterion can be established. A case study is presented where the SFRA indices along with short circuit reactance measurements, of a transformer tested for short circuit, are presented and compared.

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