NOISE AND DENOISING METHODS FOR MEASURED FREQUENCY RESPONSE SIGNALS OF POWER TRANSFORMERS

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Abstract: The work of supporting users in the field of frequency response analysis (FRA) to diagnose and assess mechanical deformations and electrical failures on the active part of power transformers efficiently and automatically is now required and shown to be very necessary. One of important things needs to be done is denoising the frequency response signals while saving useful information of original signals for later relevant algorithms. Sometimes a compromise between these two requirements at certain frequencies is unavoidable since at these frequencies, the noise is mixed with useful information of measured signals.

The paper's contribution aims to introduce frequency response signals of power transformer, together with corresponding noise sources and relevant software-based denoising methods. Appropriate methods are proposed in accordance with noise types. The paper also belongs to a series of research tasks which will deal with the issue of automatic and intelligent interpretation of FRA measurements for power transformers.

1 INTRODUCTION

Frequency Response Analysis (FRA) technique recently gains a high attention from a large number of users in the field of diagnosis and assessment of mechanical deformations and electrical failures on the active part of power transformers. However, due to the fact that there are no formal relevant standards which can help users to interpret the FRA results in detail, a need of an automatic and intelligent tool for supporting them is required. This tool must based on knowledge mentioned in current draft formal standards such as Chinese standard [1], CIGRE [2], IEC [3] and IEEE [4].

For such an automatic and intelligent tool, the input signal processing is of course very essential. This process aims to make the signal waveform smoothed, if it "ripples", and to extract useful information for the diagnosis interpretation stage, including denoising signals as pre-processing step. Although it is not usual to observe noise in FRA measurement results, references [5, 6] and others show that there is noise in measured frequency response signals in some certain situations. Therefore, the denoising pre-processing stage is worthy to investigate.

In general there are three types of denoising methods applied for frequency response signals: hardware-, software- and measurement-technique-based methods [5]. Among them, the software-based denoising method is of importance since it is the last solution used to fix the noise problem. Thus, this paper focuses on software-based methods for the purpose of denoising frequency response signals measured on power transformers.

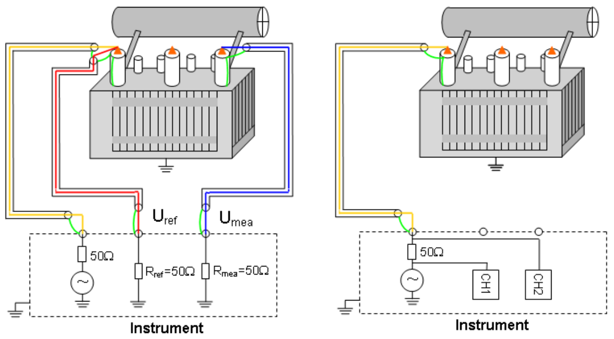
The test objects of this article includes a two-winding 200 kVA 10,4/0,4 kV Yz5 opened distribution transformer, and a few power transformers which have noise in measured frequency response (FR) signals, from a large FRA database with more than 600 transformers.

2 FREQUENCY RESPONSE SIGNALS

In this section two main types of frequency response signals, i.e. "standard" FRA and terminal FR, measured on tested transformers will be presented as source signals for the main part.

To measure FR signals, there are two main methods. The first one uses Ohm-law-based measuring instruments, e.g. network analyzer HP4195A [7], to measure voltages/currents at transformer terminals and then calculate the responses whereas in the second one, the wave-reflection-based measuring instrument, e.g. vector-network analyzer (VNA) FRAnalyzer [5], is utilised to output automatically the signals. It seems that there is more noise with regard to the VNA-type instrument while the accuracy and comfortableness of them in most cases are out of our reach. However, we here work with only FR signals measured through schemes shown in

Figure 1 via a VNA instrument, which is mentioned in current standards.



(a) FRA test (b) Terminal FR test

Figure 1: FR measurement schemes

2.1 “Standard” FRA signals

The so-called standard FRA measurements defined in above-mentioned standards, i.e. [1-4], consist of four types of fundamental FRA measurements as follows:

- End-to-end test (EE)
- End-to-end short-circuit test (EESC)
- Capacitive inter-winding test (CAP)
- Inductive inter-winding test (IND)

The standard FRA measuring scheme for the distribution transformer and corresponding measured signals are illustrated in Figures 1a and 2.

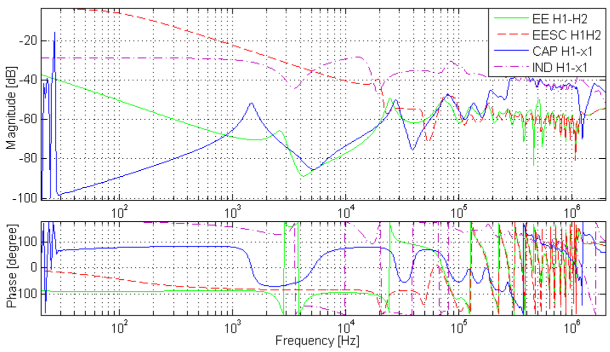


Figure 2: Standard FRA signals

2.2 Terminal FR signals

Terminal frequency response signals are under driving-point impedance/admittance, transfer impedance and voltage gain forms. Those signals can be employed in different applications for power transformers.

Figure 1b shows a measurement scheme for measuring the frequency behaviour of the impedance (driving point impedance) of transformer windings. The voltage gain can also be measured through the configuration in Figure 1a with CH1-channel as a reference channel [8]. Figure 3 presents corresponding results derived from the scheme of Figures 1a and 1b.

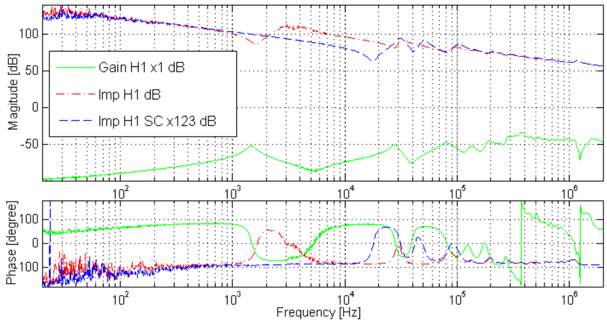


Figure 3: Terminal FR signals of a transformer

3 NOISE CLASSIFICATION

In general there are several sources of noises presenting in FR signals. Three main sources are from power frequency interference to the measurement setup (narrowband), from the instrument itself (wideband), and from the interaction of characteristics between the device under tests (DUT) and measurement types (narrowband).

3.1 Noise from power frequency range interference

Power frequency range noise appears when measurements are performed onsite in substations with high electromagnetic fields (live bus bars with rated voltages above 380 kV) and nearby energized equipments. This kind of noise depends also on the size of windings, presents in narrowband, between 30 Hz and 100 Hz, and at harmonic frequencies [5]. Figure 4 depicts those noises in FRA signals.

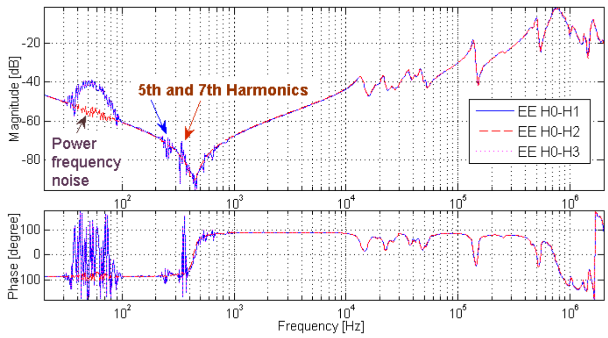


Figure 4: Power frequency range noises in FRA signals of a 500 kV winding

3.2 Noise from instrument-related distortion

This type of noise, also called as noise floor [5], occurs when measuring responses are out of the limited dynamic range of the instrument. From [2], the requirement of the minimum dynamic range of 120 dB (from -100 dB to + 20 dB) for FRA instruments is suggested. An example of noise floor phenomenon with a terminal FR signal was observed in Figure 3.

3.3 Noise from the DUT and measurement type

This noise type appears normally when one performs measurements on transformers with high magnetizing inductance, delta-connected windings, or in the capacitive FRA test configuration [5]. On another hand, if the measuring circuit in terminal FR measurement scheme has more opened-circuited terminals, more noise takes place.

Figure 2 depicts a narrowband noise from the capacitive FRA measurement on a transformer. From this figure, one can observe that only the capacitive test has noise while the others have no noise even if they all are conducted under the same measurement technique and condition.

3.4 Noise from other sources

Noise also appears if the measurement setup is carried out under some conditions in which the interference from surrounding environment is unavoidable, e.g. from communication signals or corona discharges, but this phenomenon is hardly found in FRA results [5]. Besides, the so-called measurement technique by mistake that installs bad grounding or makes measuring circuit short-circuited or establishes unappropriate instrument settings etc. in measuring FR signals also generates noise.

3.5 Summary

Although several noise sources are introduced, in the viewpoint of denoising technique, there are only two main noise kinds defined as follows:

1. Linear-range noise: Noise takes place in the linear behaviour of frequency responses and mainly is power frequency range interference.
2. Nonlinear-range noise: Noise occurs in ranges of frequency responses, in which the linear behaviour is not found.

Our results later will confirm this denoising-technique-based classification of noise, no matter how the real noises are. For illustration, let have a look on trace H0-H1 in Figure 4, the noise in low frequency range might be not white-noise with no-zero mean, and the denoising solution for non-white-noise in general has not been published yet. However, by simply linear interpolation the true signal can be derived as we all know that there is a linear behaviour here.

4 SOFTWARE-BASED DENOISING METHOD

We explore the possibility of using different methods to denoise FR signals with two main above-defined noise kinds. The goal of this part is to suppress the noise in the signal while maintaining helpful information such as linear behaviour of magnitude/phase as well as resonance/anti-resonance conditions, for the purpose of diagnosis interpretation.

In regard with the linear range noise, the method of low-order interpolation/fitting seems to be good enough. However, for the nonlinear range noise, the combination of several methods is required. Here we only focus on the wavelet-based solution since it has been one of the main denoising methods recently, and it has been not available for such noise types.

4.1 Low-order interpolation/fitting

These methods are the best available solutions for linear range noise in standard FRA signals. To reach the best performance, one has to eliminate all clear-noise out of the signal and hold "representative" data which will later belong to the interpolated/fitted signal. Figure 5 and Table 1 show denoising result and its "goodness of fit" indexes [9] for an end-to-end FRA signal of a 500 kV HV winding. Although statistical indicators for phase signal are not perfect as those from magnitude due to its bigger variance, satisfied denoising signals are derived.

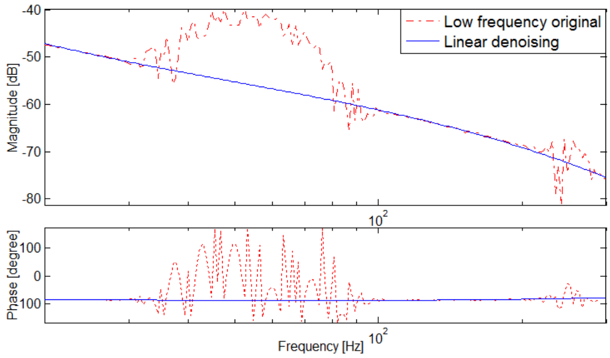


Figure 5: Linear range noise and denoising

Table 1: Goodness-of-fit indexes

Index	Magnitude in dB	Phase in °
sse	4.3289	112.7370
rmse	0.2402	1.2260
rsquare	0.9992	0.7028
rsquare-adjusted	0.9992	0.6909

4.2 Smoothing of measured waveform

Smoothing of the waveform is recommended as a first step in the pre-processing stage when ripples in measured signals are observed. Besides, for the purpose of denoising signals in a nonlinear range, this work is also required to generate an objective signal. Since there is no general rule for recognizing noise in most of our cases because of diversity of real noise forms, this objective version can be considered as the "less noisy" or reference denoised signal.

Depending on selecting parameters and available methods [9], the smoothed signal may be "smooth" or "oscillate". Figure 6 illustrates different smoothed versions of an end-to-end FRA signal of a transformer winding. It can be concluded that if a version is smooth, it contains little high-frequency components and vice versa.

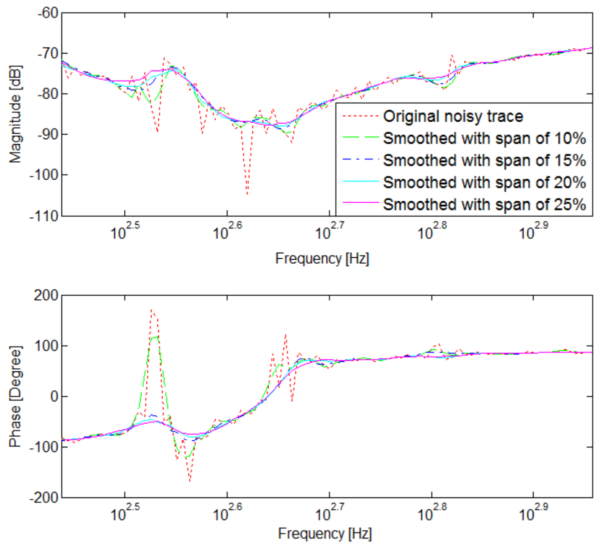


Figure 6: Nonlinear range noisy signal and its smoothed versions

4.3 Wavelet-based noise filter

The solution of wavelet-based filter for denoising signals is found nearly the best among transformation-based filters if the input signal is not the sine-shape wave. Unlike basic Fourier transformation, Wavelet transform does not lose information of signals, which has the same frequency with noise.

Here we summarize important information from an illustration in [10] in order to present our way to denoise FR signals. Other fundamental concepts of wavelet technique can be found in any wavelet text-book.

4.3.1 One-stage filtering

A specific wavelet, together with its scaling function, plays a role of low- and high-pass filters if they fulfill the requirement of a quadrature mirror filter (qmf). After being filtered through such wavelet, a signal (S) is decomposed into two components: approximation (A) and detail (D) signals. The A- and D-signals are the low- and high-frequency components of the original S respectively as shown in Figure 7a. Actually, in all algorithms, A- and D-coefficients are derived after the transform instead of A- and D-signals, but the same meaning is hold.

4.3.2 Multiple-level decomposition

Depending mainly on the nature of signals, they can be decomposed level-by-level as depicted in Figure 7b. The original signal S can be decomposed as sum of an A-version at a decomposition level j^{th} and D-versions from j^{th} level to the first level.

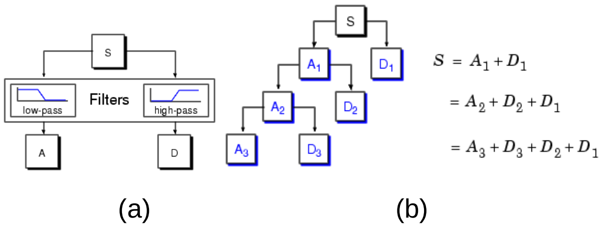


Figure 7: Multiple-stage decomposition [10]

In Figure 7b, the first level D_1 contains the highest frequency components of the signal, and the second level D_2 consists of the highest frequency contents of A_1, and so on. Therefore, if N is the number of decomposition levels, then A_N has lowest frequency components while D_1 has highest frequencies oscillations from the original.

4.3.3 Denoising procedure

In order to suppress high-frequency noise in a signal, appropriate thresholds at decomposition levels should be determined in order to removing coefficients due to noise (by setting to zero if they are lower than a relevant threshold value) and holding coefficients from the original signal. Figure 8 presents an example of denoising a signal. On the left there are N = 3 decomposition levels and three thresholds being applied for three sets of detail coefficients (d_1, d_2 and d_3) which are derived after discrete wavelet transform with base wavelet db3. On the right of this figure, original and thresholded coefficients at all levels as well as original and denoised signals are observed. The denoised signal is composed from thresholded coefficients after inverse wavelet transform.

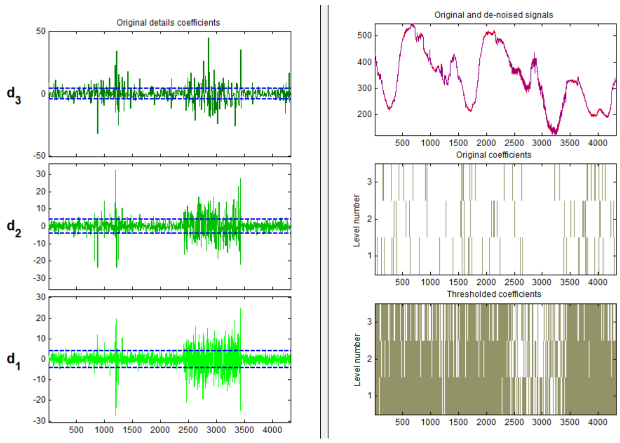


Figure 8: Thresholding detail coefficients [10]

There have been several available thresholding methods proposed for uniform white noise; but for unscaled white noise or non-white noise there has been no general solution. Since we treat these noise types as nonlinear range noise, then this noise can be suppressed in an easy way of thresholding thanks to the smoothed reference version of a noisy signal.

4.3.4 Method for denoising FR signals

Several input parameters necessary for a wavelet-based denoising solution are:

- A base wavelet acts as a qmf
- A number of decomposition levels (N)
- A suitable thresholding method

An appropriate base wavelet which will maximize coefficients makes the thresholding step more convenient. In case the objective signal, or noise type, e.g. white noise, is known, the optimal wavelet can be chosen through correlation calculation with the objective signal [11, 12]. In addition, an improvement on selecting optimally a set of both wavelet and decomposition level through energy principle was proposed [12]. We combine those principles with an adjustment as below mentioned to denoise our signals.

The adjustment is made based on a fact that our objective signals will not contain any high-frequency component from the original one. Therefore, an easy but effective thresholding method is implemented by setting all detail coefficients to zero, i.e. assigning thresholds as the maximum corresponding values of coefficients level-by-level, in order to get only the approximation signal. An iteration algorithm is then implemented in searching the similarity between the approximation signal at a decomposition level and the objective signal which can be considered as one of the smoothed versions in section 4.2, when the level is increased gradually to the maximum value. In case the similarity is found, the corresponding approximation signal is considered as a potential denoised signal.

Based on this argument, combinations of wavelets and decomposition levels are ranked through the maximum cross correlation coefficients between the objective signal and the approximation signal at each decomposition level ($n \leq N$). In case a set of a base wavelet and a decomposition level yields a high value of correlation coefficient, this set is chosen as an alternative. The highest value of correlation coefficient does not mean the best solution, since the smoothed objective signal is not perfect, but one can find the best denoised signal in the top of the ranking list.

4.3.5 Results

We collect families of orthogonal wavelets fulfilling the qmf requirement: daubechies (db1÷db20), symlets (sym1÷sym20) and coiflets (coif1÷coif5) for a base wavelet library for our iteration algorithm. The maximum value of decomposition level is calculated automatically based on sample number of the noisy signal, which was resampled in advance for a better resolution. To show the effectiveness of the algorithm for two above-defined noise types, we report the denoising solutions for two typical cases with narrowband noise in a standard end-to-end FRA signal and wideband noise in a terminal FR signal, which can be followed in Figure 9 / Table 2 and Figure 10 / Table 3 respectively.

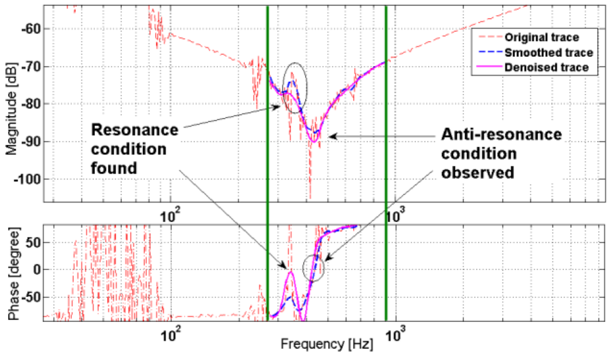


Figure 9: A denoising solution in narrowband nonlinear range of a FRA signal

Table 2: Four optimal selections of base wavelet and decomposition level for the magnitude signal in Figure 9.

Solution No.	Wavelet	Dec. level	Corr. coeff.
1	db10	6	0.8764
2	db6	6	0.8509
3	sym9	6	0.8232
4	sym4	8	0.7985

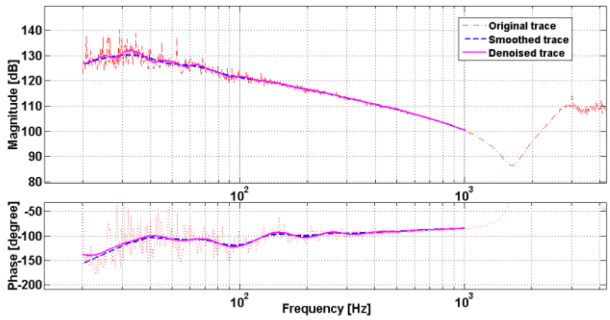


Figure 10: A denoising solution in wideband nonlinear range of a FR signal at low frequencies

Table 3: Four optimal selections of base wavelet and decomposition level number for the magnitude signal in Figure 10.

Solution No.	Wavelet	Dec. level	Corr. coeff.
1	sym5	5	0.9967
2	db2	5	0.9961
3	sym2	5	0.9961
4	db12	5	0.9944

From Figure 9, it can be concluded from our experience that with an appropriate smoothed version of a noisy signal acting as an object for the optimal calculation of wavelet and decomposition level, several good wavelet-based denoised solutions are achieved. In particular, the denoised signal in this case recovers both resonance and anti-resonance conditions, which can not be confirmed efficiently through any version of smoothed signal in Figure 6. However, it seems that further quantitative analysis on what frequency and magnitude/phase at those conditions need information from both smoothed and denoised signals since the real signal and the noise are mixed. In such case a compromise could be one of alternatives.

Figure 10 and Table 3 depict results when a wideband nonlinear range noise occurs in a terminal FR signal of a transformer. Both smoothed and denoised signals can be considered as final results for the denoising problem.

5 CONCLUSIONS

In this contribution, an overview of noise types based on denoising viewpoint and effective denoising methods for measured FR signals of power transformers is presented. In detail, applications of denoising methods in accordance with each type of noise are proposed.

Experiments on our cases verify the effectiveness of the denoising-technique-based classification of noise in our signals. Most noise, determined later from noisy signals and their denoised versions, is not uniform white noise, which can be verified through their power spectral densities. The general solution for those noise types has not been achieved until now.

The linear range noise can be suppressed thanks to low-order interpolation/fitting methods. Although this noise type mainly occurs in the end-to-end FRA test, it can also be observed in other tests. Of course the noise in any test can be eliminated effectively.

The nonlinear range noise may appear in signals of many FRA and terminal FR measurements; and for fixing this problem, a wavelet-based denoising method is proposed. According to the method, after a reference/objective signal is selected through smoothing, a reasonable denoised signal can be reached. As shown in illustrated cases, experiments on other cases also confirm that quantitative analysis on determining final denoised signal needs information from both smoothed and wavelet-based denoised signals, especially when the *low frequency* noise is mixed with the signal in low frequency range.

In general, the nonlinear range noise could be suppressed through other methods such as fuzzy filter-based or transfer function approximation etc. However, our solution seems to be good enough for an alternative. In several cases, the best thing is of course to make the measurement as perfect as possible.

6 ACKNOWLEDGMENTS

The main author wishes to acknowledge Omicron electronics GmbH, Austria, for the database for the research. In addition, comments from Dr. Dung T. Vo, University of California at San Diego, La Jolla, CA, USA, are highly appreciated.

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