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Effect of Terminating and Shunt Resistors on the FRA Method Sensitivity

M. H. Samimi, S. Tenbohlen
Institute of Power Transmission and High Voltage Technology (IEH)
Universität Stuttgart
Stuttgart, Germany

A. A. Shayegani Akmal, H. Mohseni
High Voltage Institute, ECE Department
Faculty of Engineering, University of Tehran
Tehran, Iran

***Abstract*—Frequency Response Analysis (FRA) method proved to be very useful in detecting the mechanical deformations inside a power transformer. Several configurations are possible for FRA method and it is better to use the one with the best sensitivity to mechanical changes. In this paper, the effect of terminating resistors on the FRA traces is studied in order to find the most sensitive ones. The sensitivity to disc space variation, which is a common mechanical defect, is studied particularly. Four usual connection methods are used with 12 different resistor pairs in an experimental setup. In order to perform the sensitivity analysis, three numerical indices are employed. The results and general conclusions are provided regarding the use of terminating resistors, but more research need to be conducted for other typical mechanical variations in power transformers.**

Keywords*—fault diagnosis; frequency response; power transformer testing; sensitivity; transfer functions; transformer windings.

I. Introduction

Power transformers are one of the most important items in power systems and their reliability is of great concern. Outage of a transformer can impose high expenditures to the power system manager because of time-out and repair of the transformer. One of the events that can cause transformer failure is short-circuit. Great electromagnetic forces which are due to the high currents in the transformer windings can change the mechanical geometry of the windings [1]. Accidents during transportation as well as tap-changer failure can also cause mechanical deformations [2]. The mechanical damage may not lead to direct failure of the transformer, but in case of severe damage, it may lead to consecutive electrical failure after re-energize. Therefore, it is necessary to detect these destructive damages beforehand. Transfer Function (TF) assessment using well-known frequency response analysis (FRA) method is a powerful diagnostic tool which helps to detect mechanical changes inside a transformer.

The FRA technique provides useful and reliable information about the mechanical situation of the transformer windings and many researchers have focused on this field recently [1-12]. FRA method makes it possible to find out about the windings mechanical condition without opening the transformer tank and visual inspection. However, there is still a lack of scientific algorithms to interpret the results automatically and therefore the interpretation has been done by experts intuitively. To reach a reliable algorithm for assessing the mechanical condition of the transformer windings, the main efforts in this area are devoted to the interpretation of the FRA results [10, 13-15].

The interpretation researches are conducted in distinct fields. In the first field, an equivalent circuit is used to reproduce the frequency behavior of the transformer [16-20]. Subsequently, the changes, which are related to different mechanical deformations, are applied to the circuit elements. Then, by comparing the transformer FRA trace with the one generated from the equivalent circuit, the deformation type and severity can be distinguished [5, 6, 21]. In the second field, researchers use the mathematical models in which the TF is represented by rational functions and the deformation is realized based on the variations in the poles and zeros of the rational function [22-24]. The third field is characterized by numerical indices; an index extracted from two FRA traces can show the amount of mechanical variation inside the transformer [25-29]. The last field includes the winding modeling and estimation of the winding frequency behavior in mechanical deformations using traveling wave theory [8].

Along with these interpretation researches, some studies try to realize the effect of different factors on the FRA traces [30-35]. These factors include insulation contamination, moisture, temperature, core magnetization, insulation aging, and measurement configurations [4, 7, 9, 36-39]. Understanding the effects of these factors is needed because without knowing their effects, an alteration in these factors may show itself as a mechanical change leading to false interpretation of the results. Moreover, good understanding of the effects helps to standardize the measuring procedure leading to reproducible results which the interpretation is not possible without them.

It is also important to use the measuring connections with higher sensitivity to mechanical variations. The reason is that the results experience more distinct changes, and this simplifies the interpretation. In the measurement configuration, two resistors are used for cable termination. The main goal of this paper is to find the resistor pair that has the best sensitivity for detecting the Disc Space Variation (DSV) in a transformer winding.

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The effect of shunt resistors on the FRA traces has been studied previously, but the shunt resistor is used for measuring the current signal in FRA measurement and is different from terminating resistors [9, 39]. Reference [40] clearly states: "at the present time, there is no technical evidence of any particular impedance value being of greater benefit for the detection of winding displacement." This paper focuses on different terminating resistors and shunts to find out which resistor pair has the best sensitivity to DSV.

First, the experimental setup is explained. Then, three numerical indices used for performing the sensitivity analysis are addressed. Afterward, the results are presented and discussed. General rules regarding the resistor usage are explained as well as sensitivity comparison of them to DSV. Finally, the conclusion section summarizes the findings in this paper.

II. Experimental Setup

For sensitivity analysis, a High Voltage (HV) winding with 60 discs, 11 turns in each disc, and a 24-turn helical Low Voltage (LV) winding, 12 parallel conductors in each turn, are used as the test setup. The windings have the construction of transformer windings with a rated voltage of approximately 10 kV and a rated output of 1.3 MVA. Fig. 1 shows the diagram of the windings. Two aluminum cylinders are also used in the setup to model the core and tank potential of the transformer. Both of these cylinders are connected to the common ground of the setup. Two grounding plates have also been used in the bottom and top of the windings to complete the core and tank potentials.

The both ends of the windings are available and can be grounded or left floating. In this paper, four more usual FRA connections are used, Fig. 2. The arrow in Fig. 2 shows the point in which the signal is injected. V_R represents the Reference Voltage, and V_M stands for the Measurement Voltage. In all the connections, the ratio of V_M to V_R is kept as the frequency response of the windings. The connections in Fig. 2 are known as:

(a) end-to-end,

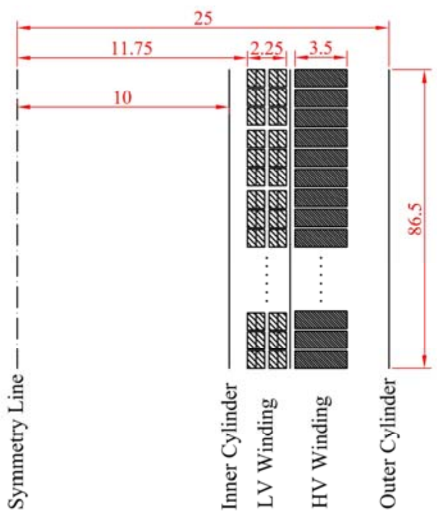

Fig. 1. Diagram of the experimental setup. The dimentions are in Cm.

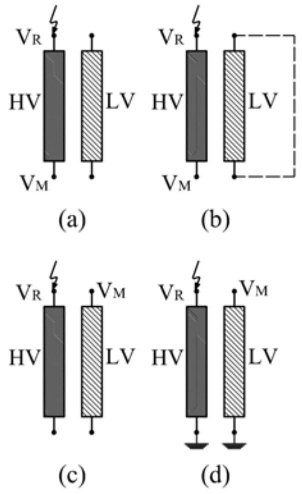

Fig. 2. The FRA connections used for sensitivity analysis.

(b) end-to-end short-circuit,
(c) capacitive inter-winding, and
(d) inductive inter-winding

in the literature [40]. These are the connections which are recommended to be used for FRA method and this paper focuses on these configurations as well.

The TF measurement is done with the SFRA method [40] using OMICRON FRAnalyser™. The measurements are performed from 40 Hz to 2 MHz, which is the recommended range in the literature. The data above 2 MHz shows good sensitivity to mechanical changes, but has the reproducibility problem. 1400 samples are captured in the frequency range and these points are distributed logarithmically.

Coaxial cables are used for connecting the measurement device to the windings. One end of the cables needs to be terminated with resistors. These resistors placed between the cable end and its grounded shield. The input impedance of the device can be chosen to be 50 Ω or 1 MΩ. Different resistors can be chosen as shunt resistors on the transformer side. In this paper, 6 resistors with values of 5 Ω, 15 Ω, 50 Ω, 100 Ω, 1.137 kΩ, and 1 MΩ are used for shunts. Accounting the two input possibility of the device, 12 traces are captured for each connection. Fig. 3 shows the whole test setup along with terminating resistors.

Besides the comparison of the traces for the healthy windings, a disc space variation applied to the HV winding to investigate which resistor pair has the best sensitivity to this mechanical change. The two discs from the upper part of the HV winding are shifted with 3 different spacers with 5, 10, and 15 mm width. As a result, there are four sets of measurements for each connection which are related to no shift, and 5, 10, 15 mm shift of the two discs. The results and their comparison are presented in the next sections.

III. Numerical Indices for Sensitivity Analysis

For doing the sensitivity analysis between different resistor pairs, three numerical indices are used. Reference [11] has compared the sensitivity of different FRA connections to various mechanical deformations. This reference has only

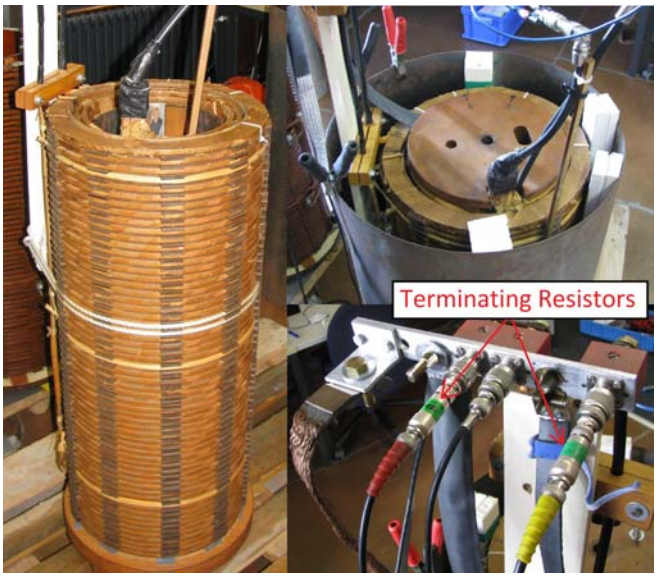

Fig. 3. Experimental setup; HV and LV winding (left); windings inside the outer cylinder (top right); conncetion cables with terminating resistors (bottom right).

used the visual comparison which is not accurate enough. Using numbers eases the comparison procedure and leads to more precise results. Because of this reason, numerical indices are employed here.

Different numerical indices are proposed for interpretation in the literature. For sensitivity comparison, the changes of the FRA trace with respect to its reference fingerprint are important and therefore, three indices are used which shows the movement of curves in the best way.

The first index is the well-known Correlation Coefficient (CC). *CC* can be calculated using (1):

$$CC_{(X,Y)} = \frac{\sum_{i=1}^{N} X(i)Y(i)}{\sqrt{\sum_{i=1}^{N}[X(i)]^2 \sum_{i=1}^{N}[Y(i)]^2}}, \qquad (1)$$

where $X(i)$ and $Y(i)$ are the ith elements of the reference fingerprints and measured frequency response respectively. The index addressed in this paper is $1-CC$. This index shows how much the measured FRA trace is different from the source fingerprint in the shape. If the two traces will be identical, *CC* equals 1 and the index $1-CC$ equals zero. As the shape of the traces changes, *CC* becomes less than 1 and $1-CC$ starts to increase. It changes between 0 and 1. Larger amount of $1-CC$ indicates more shape difference between the two traces.

Using the CC alone is not enough. The reason lies in the fact that if a trace shifts up or down without changes in the shape, the CC remains 1 and cannot show this difference. To overcome this deficiency, a second index is employed, which is called Euclidean Distance (ED). *ED* presents how much the distance between the measured trace and the fingerprint is. If the shape does not change at all, this index can still show the shift of the curves. *ED* has been shown to have also a linear relationship to mechanical deformation extent in some cases [41]. *ED* can be calculated using (2):

$$ED = \|X - Y\| = \sqrt{(X-Y)^T(X-Y)}, \qquad (2)$$

where $X = [x_1, x_2, ..., x_n]$ and $Y = [y_1, y_2, ..., y_n]$ are the two FRA vectors with *n* elements and *T* stands for the transpose of the vector. Higher *ED* indicates more shift of the trace with respect to the fingerprint.

There are numbers of indices in the literature which are based on resonance and anti-resonance points; how much their frequency and amplitude are changed respected to each other. The amplitude variation is included in *ED* index, but for the frequency shifts a third index is required. This index is called Index of Frequency Deviation (IFD) and can be calculated using (3):

$$IFD = \sum_{i=1}^{M} IFD_i = \sum_{i=1}^{M} |f_{x,i} - f_{y,i}|, \qquad (3)$$

where $f_{x,i}$ and $f_{y,i}$ are the resonance or anti-resonance frequencies of the two FRA curves. In the literature, the index is divided by the resonance frequency of one curve [28]. If the index is divided, an equal shift in resonance frequencies would have higher impacts when the shift occurs at lower frequencies. This is not obviously true because the importance of resonance frequency is almost the same in the whole range of the frequency. As a result, it is better to use (3) which reflects the amount of frequency shift in Hz. Higher values mean that the resonance points are more sensitive to mechanical changes. These three indices are sufficient to show the sensitivity of the FRA curves.

The first two indices can be calculated easily using the vectors of FRA measurement, but for the last index the resonance and anti-resonance frequencies should be discriminated first. Finding these frequencies is not simple because the traces have plenty of local maximums and minimums due to noise in the measurement. Different ideas have been proposed up to now for resonance detection, but this paper uses the one proposed in [42]. This reference uses four criteria to find the resonance points:

- maxima and minima have to resist a smoothing behavior,
- the area under a resonance rise, bounded by nearby minima, should have a minimum threshold value,
- the frequency separation between neighbor maxima and minima should have a minimum threshold value,
- the distance of maxima and minima values should exceed a minimum threshold value.

More detailed information can be found in [42].

IV. Results and Discussion

A. Effect of different resistor pairs on FRA measurement

First, the different traces measured in one winding mechanical condition are reported. Fig. 4 shows the different curves for connection (d). Similar traces are captured for other

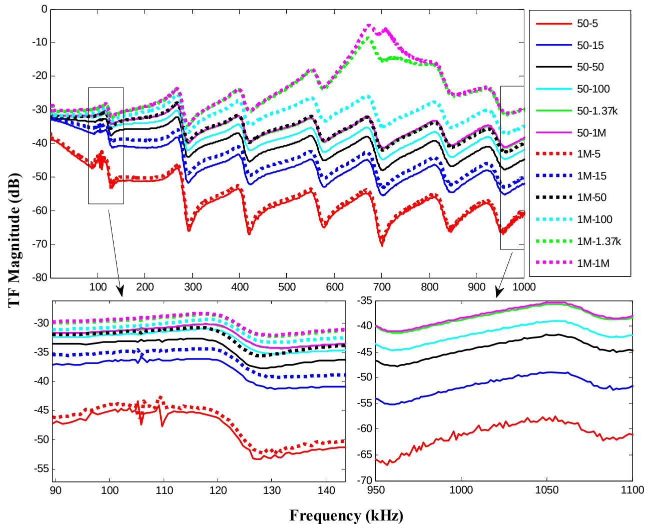

Fig. 4. Results of FRA for inductive inter-winding with different terminating resistors. The names indicates the terminating resitor pairs: the left numbers are the input resistance of the device in Ohm and the right ones are the terminating resistors in transformer side.

connections as well, but for simplicity only one of them is reported here.

From Fig. 4 it is obvious that when the terminating and shunt resistors have larger values, the amplitude of the recorded curve is higher. In case of background noise during measurement, especially in a high-voltage substation, higher amplitudes are preferred due to more immunity to the noise. Therefore, it is better to use higher resistors leading to larger amplitudes.

More than the aforementioned reason, traces with the lower resistors are also not smooth. Back to the insets of Fig. 4, it can be seen that the 50-5 Ω of terminating and shunt resistors are not very smooth. Plenty of local resonances can be seen in the curve making the subsequent interpretation difficult. However, using lower resistors leads to some resonances which fade away with higher resistors. An example can be seen in fig. 4 between 100 and 110 kHz. Two resonances can be seen between 100 and 110 kHz, which are only visible with 5 and 15 Ω resistors. Though, because of noises on the lower resistors, it is better not to measure the FRA traces with low terminating and shunt resistors. 50 Ω and above seems to be suitable resistors for FRA method.

It is also noteworthy that when the resistors are small, the changes in them cause more alterations in the curve amplitude, whereas with higher resistors the changes become smaller. It is also visible from Fig. 4. Because of this reason, it is suggested not to use small resistors. In case of small resistors, the unavoidable changes in resistor values between two measurements due to aging, cause more error in the measurement and the interpretation subsequently. In summary, using resistors less than 50 Ω is not recommended.

B. Sensitivity of different resistor pairs to DSV

Fig. 5 shows the FRA traces for 0 and 15 mm DSV for three selected resistor pairs. The traces for connections (a) and

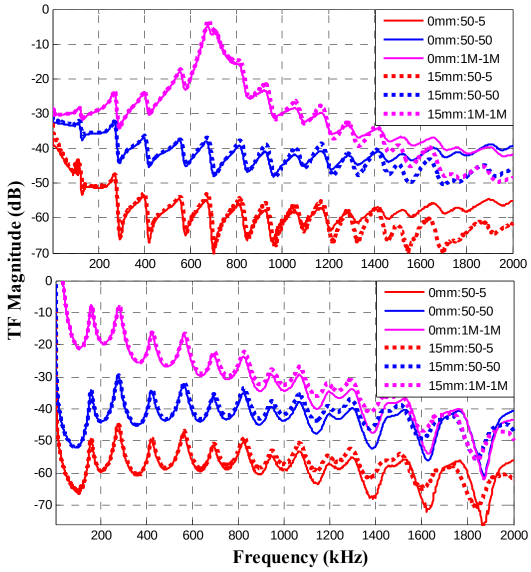

Fig. 5. Results of FRA for some of terminating resistors for 0 and 15 mm DSV for inductive inter-winding (top) and end-to-end (bottom) connections.

(d) are shown. As it can be seen, it is quite impossible to make a judgment regarding the sensitivity only by visual investigation. As a result, three mentioned indices are used to make a comparison between resistor pairs.

The first and second indices, *1-CC* and *ED* are calculated for two frequency ranges: 100-1000 kHz and 1-2 MHz. The reason is the high-frequency content is not practical in all applications. As an example, for transformers with large bushings, the frequency response above 1 MHz does not have sufficient repeatability and therefore, is not practical. The third index, *IFD*, is calculated for 100-1000 kHz. The results for all of the tested connections are provided in table I to IV. The indices are addressed for different resistor pairs in each table. For simplicity, only the indices which are extracted from the 0 and 15 mm traces are reported in this paper. The next paragraphs summarize some interesting points about the results.

Comparing the four tables to each other, it is obvious that higher resistors are preferable for all the connections.

TABLE I. SENSITIVITY ANALYSIS TO DSV FOR END-TO-END CONFIGURATION

Resistor Pair Ω	*1-CC* ($\times 10^{-3}$)		*ED*		*IFD*
	100-1000 kHz	*1-2 MHz*	*100-1000 kHz*	*1-2 MHz*	*100-1000 kHz*
50-5	0.1205	1.4952	29.2493	77.3348	24.93
50-15	0.1590	2.0332	28.9667	77.6525	29.59
50-50	0.2130	2.7449	28.6846	77.8904	31.13
50-100	0.2469	3.0933	28.8398	77.7107	32.76
50-1.37 k	0.2966	3.6666	28.9164	77.6064	36.59
50-1 M	0.3041	3.7168	28.9350	77.5071	35.49
1 M-5	0.1203	1.5261	29.1484	77.6182	29.39
1 M-15	0.1731	2.1511	29.0355	77.8531	34.40
1 M-50	0.2707	2.9438	28.7938	78.0145	36.57
1 M-100	0.3493	3.2100	28.8935	77.8817	36.85
1 M-1.37 k	0.4379	3.3730	28.7019	77.6992	35.54
1 M-1 M	0.4487	3.3711	28.7310	77.6022	36.43

TABLE II. SENSITIVITY ANALYSIS TO DSV FOR END-TO-END SHORT-CIRCUIT CONFIGURATION

Resistor Pair Ω	1-CC (×10⁻³)		ED		IFD
	100-1000 kHz	1-2 MHz	100-1000 kHz	1-2 MHz	100-1000 kHz
50-5	0.1132	1.1308	29.2640	68.5737	39.38
50-15	0.1517	1.5462	29.0180	68.8079	37.12
50-50	0.2334	2.3496	28.1613	68.7330	40.00
50-100	0.2845	2.7889	28.9849	68.7354	39.62
50-1.37 k	0.2749	2.8327	29.0326	68.6413	36.66
50-1 M	1.0183	3.0263	29.1829	68.6490	35.76
1 M-5	0.1154	1.1570	29.2699	68.7443	32.06
1 M-15	0.1656	1.6330	29.1167	68.9232	37.59
1 M-50	0.3276	2.4650	29.2183	68.8105	37.70
1 M-100	0.4078	2.5949	29.0056	68.9180	35.66
1 M-1.37 k	0.3936	2.5947	28.7966	68.7379	38.37
1 M-1 M	1.3070	3.2282	28.9492	68.6893	39.82

For end-to-end connection, table I, it is obvious that higher resistors cause more changes to the shape of the curve in DSV, but no significant change occurs in the *ED* index. Furthermore, the higher terminating resistors make the resonance points move more. The situation is same for both of the frequency bands. It can be concluded thus that for end-to-end connection higher resistors are preferred.

The results for end-to-end short-circuit method are very similar. Paying careful attention to table II shows that the best sensitivity happens when the terminating resistor on the transformer side is 1 MΩ; however, the 50 Ω resistor shows the best movement of the resonance points. The difference in the lower frequency band is more substantial than the high-frequency band. As an example, *ED* and *1-CC* does not change much with resistors.

The sensitivity analysis of capacitive inter-winding connection leads to the same consequence as for end-to-end connection; the resistor pair with higher values makes the sensitivity better. Table III clearly shows that 1-1 MΩ pair has the best sensitivity in almost both the frequency bands.

The situation for inductive inter-winding connection, table IV, is not simple. The *1-CC* index shows that higher resistors lead to more variation in the shape of the curve, though the *ED* and *IFD* show that lower resistor pairs move the trace and its resonance points further. It seems that *ED* and *IFD* are more important in the interpretation rather than *1-CC [16, 21, 26-28, 41]*. Hence, it can be concluded that the terminating pair with the smallest resistors has the best sensitivity. However, it is concluded in the previous section that using resistors lower than 50 Ω is not suitable because of noise vulnerability. In summary, it seems that 50-50 Ω or 1M-50 Ω pairs are good for the inductive inter-winding connection.

TABLE III. SENSITIVITY ANALYSIS TO DSV FOR CAPACITIVE INTER-WINDING CONFIGURATION

Resistor Pair Ω	1-CC (×10⁻³)		ED		IFD
	100-1000 kHz	1-2 MHz	100-1000 kHz	1-2 MHz	100-1000 kHz
50-5	0.2200	0.8290	38.9574	39.8004	41.75
50-15	0.3729	2.4769	43.2762	65.4504	51.62
50-50	0.5162	4.5803	44.0399	77.6460	49.77
50-100	0.6119	5.9221	44.6685	86.1483	53.34
50-1.37 k	0.7354	7.0504	44.8988	87.1336	51.53
50-1 M	0.7535	7.0487	44.9377	86.3458	45.15
1 M-5	0.2320	0.9973	39.2636	44.4568	40.59
1 M-15	0.4171	3.2335	44.0654	76.2710	49.83
1 M-50	0.6639	5.9179	45.0651	91.0492	47.41
1 M-100	0.8599	7.5420	46.3363	101.9485	51.68
1 M-1.37 k	1.0849	7.9886	47.0600	101.9195	52.36
1 M-1 M	1.1072	8.0546	47.1492	101.2201	54.86

TABLE IV. SENSITIVITY ANALYSIS TO DSV FOR INDUCTIVE INTER-WINDING CONFIGURATION

Resistor Pair Ω	1-CC (×10⁻³)		ED		IFD
	100-1000 kHz	1-2 MHz	100-1000 kHz	1-2 MHz	100-1000 kHz
50-5	0.2704	1.7516	41.8214	102.5631	54.92
50-15	0.1718	2.1507	26.6795	90.6391	52.00
50-50	0.2241	2.6829	28.5003	84.2668	53.61
50-100	0.2130	3.1291	23.7405	86.0483	47.21
50-1.37 k	0.2407	3.6208	23.6645	83.9952	48.56
50-1 M	0.2470	3.6232	23.7196	82.9369	48.56
1 M-5	0.2525	1.8682	40.3477	103.8366	55.57
1 M-15	0.1753	2.3285	25.7984	91.3185	46.59
1 M-50	0.2698	2.8266	28.5875	84.7359	56.14
1 M-100	0.3058	3.0232	23.2465	86.4056	45.35
1 M-1.37 k	0.5254	3.0333	23.0009	84.2543	54.27
1 M-1 M	0.5491	2.9928	22.7530	82.8827	45.77

An implicit outcome can also be inferred. Comparing the numbers in the provided tables shows that inter-winding connections have more sensitivity to DSV than end-to-end configurations in almost all the cases. The inductive inter-winding has the best sensitivity in resonance point movement and is more suitable for interpretation algorithms based on resonance points. However, in some cases the capacitive inter-winding can be chosen as the best. It is also noteworthy that in the high-frequency band, the effects of different resistors are less than the same on the low-frequency band.

V. CONCLUSION

In this paper, different resistor pairs are used as terminating and shunt resistors for four usual FRA connections to find the best sensitivity to DSV. The below points can be summarized from the paper:

- higher resistors leads to higher amplitude of the TF and better immunity to noise,
- using resistors less than 50 Ω is not recommended because they result in a nonsmooth curve,
- the high input impedance of the device is more sensitive in all connections,
- higher terminating and shunt resistors are preferred almost for all of the connections,
- DSV has more influence on the inter-winding connections than end-to-end ones,
- for methods using the resonance and anti-resonance points and methods using the high-frequency band, the inductive inter-winding connection method has the best sensitivity to DSV,
- the effect of resistors on the sensitivity is more in the low-frequency band.

It is necessary to mention that extra survey is needed for other mechanical changes because the effect of terminating resistors on the FRA sensitivity to them may be different.

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