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Effect of Test Cable Termination on Frequency Response of Transformer Winding

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ABSTRACT- Sweep Frequency Response Analysis (SFRA) method is the most powerful tool to predict the condition of transformer winding. The reliable measurement of frequency response is equally important as its interpretation. A few standards (IEEE std. C57.149-2012, IEC 60076, the Chinese Electrical Power Industry Standard ICS27.100.F24-2005) & much research work have been published, stating dos & don'ts while measuring the frequency response of transformer winding. In this paper, an attempt is made to introduce an additional factor affecting frequency response, while doing measurements. Here, the effect of test cable termination at transformer winding terminals, to prevent signal reflection, on frequency response is presented. A possible way to select suitable value/s of terminating resistance that can correct frequency response is also proposed.

Keywords: Sweep Frequency Response Analysis (SFRA), Signal Reflection, Terminating Resistance, Characteristic Impedance, reflection co-efficient.

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1. INTRODUCTION

SWEEP Frequency Response Analysis (SFRA) is a condition monitoring tool for transformer winding deformation diagnostics. The key feature of SFRA, that it diagnoses transformer winding deformation without de-tanking, makes it popular. In 1978, the researchers E. P. Dick & C. C. Erven have introduced Frequency Response Analysis (FRA) as a tool to inspect the physical condition of transformer winding [1]. Any deformation in transformer winding may lead to a change in resistance, inductance, and capacitance associated with the location of deformation [2-3]. This change in element value is reflected in the frequency response of the winding. Hence, by comparing the responses of winding before and after deformation occurs, one may get an idea that something went nasty with the winding. Mostly the magnitude plot is referred for the diagnostic purpose [2].

Much research work under the umbrella of FRA has been published and continued. The sub areas in which these research work classified are – correct interpretation of frequency response [4-10], high frequency modelling of transformer winding that justify the frequency response [11,12], precautions which recording the frequency response [13-18]. The effectiveness of this tool depends on accurately it can measure the frequency response. *Table 1* summaries the key factors affecting the frequency response of transformer winding claimed by the literature till date. In this paper, an attempt is made to uncover an additional factor affecting the frequency response, which is not touched by the researchers in this domain before.

Table 1. Key factors affecting the frequency response of transformer winding – literature survey

Literature	Key factors affecting the frequency response of the winding
13	• shortest braid connection at the bushing • applied voltage level • settling time (dead time between two adjacent frequency components during which transformer is not energized)
14	• Value of shunt impedance, bushing, measurement lead and High voltage winding neutral connection
15	• Layout of test cable ground extension
16	• Residual magnetization, Insulating fluid, Temperature • Tap changer position and bushings • Grounding and measurement leads • Output voltage (from the test instrument) • Shorting and grounding of tertiary windings and separate neutral terminals

The frequency band of injected signal in SFRA test is quite wide, comprising low as well as high-frequency components. The high-frequency components be traveling waves and travel through coaxial cables and transformer winding. While traveling through a transmission medium (here, test cables & transformer winding) the mismatch of the characteristic impedance of transmission mediums, may reflect part of the injected signal. Due to this, the winding will interact with either fraction of injected signal or a distorted signal. The signal reflection at any terminal of the test setup may influence the frequency response of transformer winding. The termination of the transmission medium is the solution to mitigate signal reflection, the co-axial cables are terminated by 50 Ω resistor at the instrument side. There is a possibility of signal reflection at winding terminals also, and still, they are kept untouched (not terminated) while performing the test. In this paper, the effect of termination at transformer winding terminals is studied.

The paper is drafted into six sections. *Section 2* explains general test lead connections with the transformer. *Section 3* emphasizes describing the phenomenon of signal reflection from terminals of transformer winding while performing the SFRA test. In *section 4*, Frequency Response (FR) of 5 kVA and 200 kVA transformer obtained for with and without termination, also for different values of terminating resistance, are discussed. *Section 5* demonstrates a way to decide the suitable value of termination at winding ends.

2. SFRA INSTRUMENT TEST LEAD CONNECTIONS

The SFRA instrument contains an electronic circuit that outputs desired test signal, a signal processing unit, and two 50 Ω resistors. As this section aims to brief the external connection between the SFRA instrument and transformer winding, the SFRA instrument should be assumed as a black box with three terminals, namely Source, Reference, and Measure. The ‘Source’ terminal provides a test signal. It is a sweep frequency signal, having a frequency band of 20 Hz to 2 MHz, generally. The voltage magnitude of the test signal differs within the range of 2 V to 24 V, depending upon instrument providers [19]. The terminals, ‘Reference’ & ‘Measure’ collect the injected test signal and the response signal respectively, which are later used to compute the transfer function.

The ‘Source’ is connected at one of the winding terminals, generally phase terminal. The ‘Reference’ terminal is connected to the same winding end to which the ‘Source’ terminal is connected. The signal received at the remaining terminal of the winding is brought to the ‘Measure’ terminal. The ‘Source’, ‘Reference’ & ‘Measure’ on the SFRA instrument are being connected with transformer winding through co-axial cables. The co-axial cables that bring signals to ‘Reference’ & ‘Measure’ are terminated by 50 Ω resistance at the SFRA instrument [20, 22]. The earth potential required by the SFRA instrument is supplied from the transformer tank. While performing the SFRA test, to suppress electrical noise, screened (shielded) co-axial cables are used. The screen is put at earth potential.

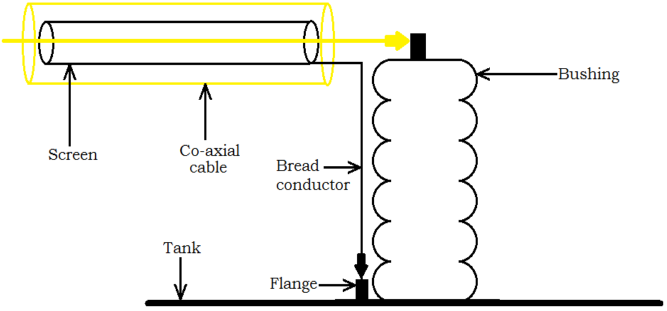

Figure 1: Schematic of earth connection for the screen of co-axial cable

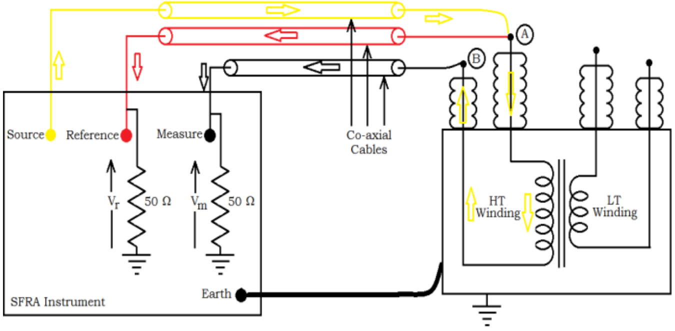

Figure 2: Connections of SFRA instrument with transformer winding

The earth potential is provided either from flange or tank, the conductor should run parallel & closer to the bushing as shown in *fig. 1*, so that reproducibility of frequency response can be attained. A glimpse of the connections discussed in this section is shown in *fig. 2*. The connections of the SFRA instrument with transformer winding are well explained in [20-23].

3. SIGNAL REFLECTION AT TRANSFORMER WINDING TERMINALS

The transformer winding can be realized by an equivalent circuit of distributed R, L, C elements as shown in *fig. 3* [24-25]. The injected test signal at the phase terminal of winding travels through the distributed network and is availed at the other terminal of the winding. The directions in which the signals travel in the test set-up are shown in *fig. 2*.

In the case of traveling signals, characteristic impedance demands special attention. A traveling signal remains undisturbed until it encounters a change in characteristic impedance. The sweep frequency (SF) signal supplied from the ‘Source’ terminal of the SFRA instrument flows through a co-axial cable and report at node ‘A’. During this travel, it experiences 50 Ω characteristic impedance. Beyond node ‘A’ the SF signal faces transformer winding, which offers characteristic impedance other than 50 Ω. The SF signal received at node ‘B’ is delivered to ‘Measure’ terminal of the SFRA instrument via co-axial cable. The characteristic impedance experienced by SF signal is again changed to 50 Ω. It is noticed that while traveling through the entire test setup, the injected test signal realizes a change in characteristic impedance twice. The value of the characteristic impedance of the co-axial cable and that of transformer winding decides, what will happen to the traveling signal? If the characteristic impedance of the cable and that of transformer winding are denoted by Z_C and Z_t respectively, then $Z_t \neq Z_C$ leads to signal reflection, while $Z_t = Z_C$ assures No signal reflection.

The signal reflection phenomenon makes the original signal traveling in a transmission medium (here co-axial cable and transformer winding) distort and at the ends of the transmission medium, part of the original signal is refracted. To prevent signal reflection, termination is provided to the transmission medium [26]. This process is called Impedance Matching. Referring to *fig. 1*, it is noticed that two resistors are connected at 'Measure' & 'Reference' terminals in the SFRA instrument, which are of value equal to the characteristic impedance of the co-axial cable. Hence, there is no possibility of signal reflection at SFRA instrument ends but there may exist at transformer winding ends (nodes 'A' and 'B'), where co-axial cables & transformer winding are connected.

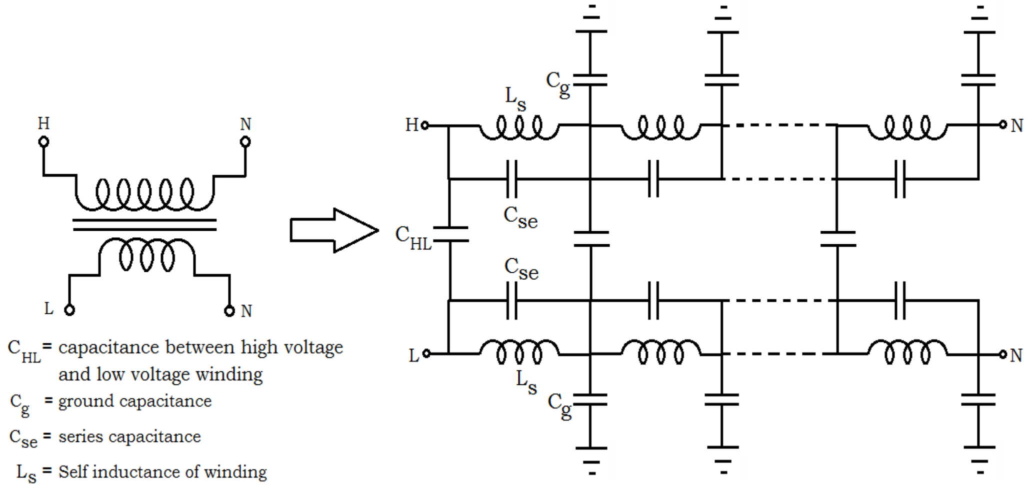

Figure 3: Equivalent circuit of Transformer Winding

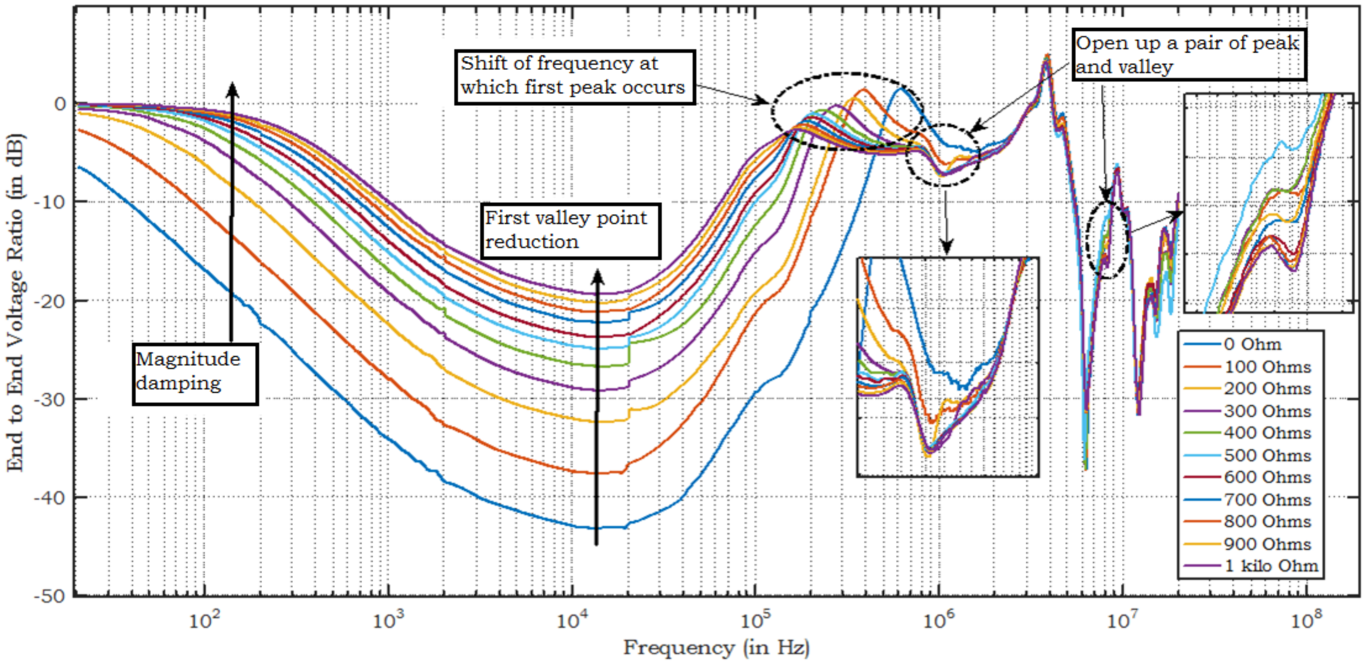

Figure 4: Frequency Response of 5 kVA transformer winding with different values of terminating resistances at node 'B'

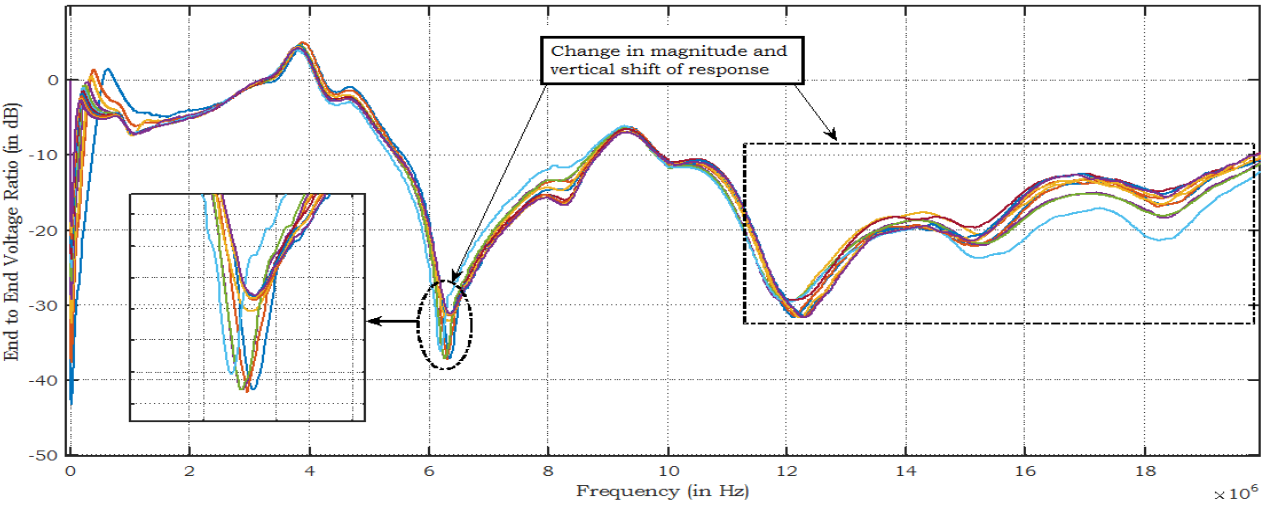

Figure 5: Frequency Response of 5 kVA transformer winding with different values of terminating resistances at node 'B' high frequency band

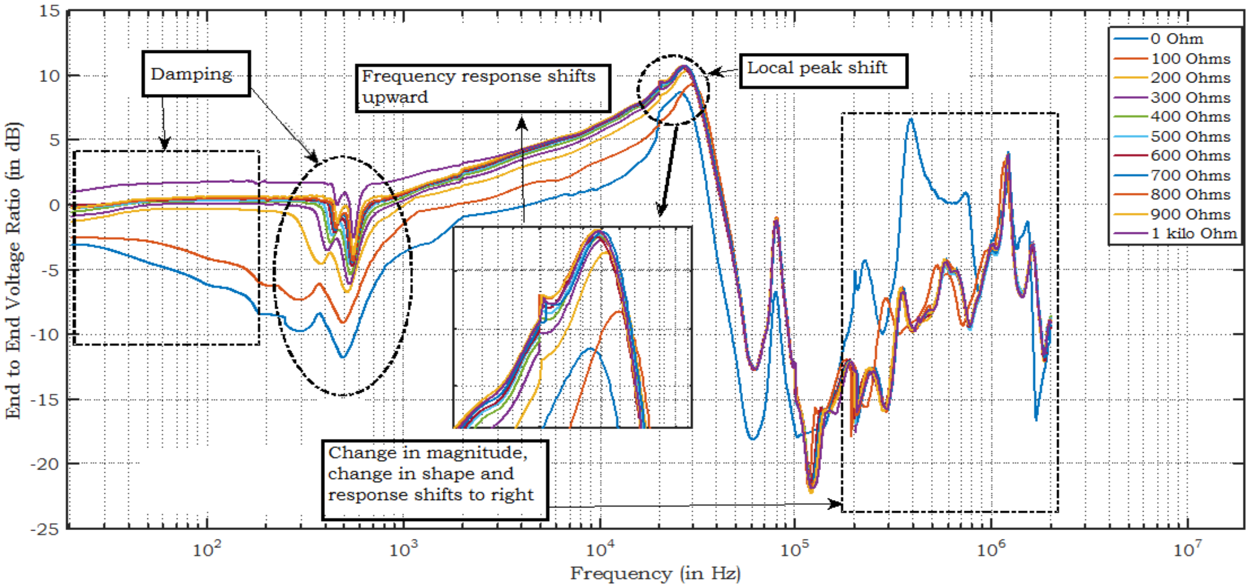

Figure 6: Frequency Response of 200 kVA transformer winding (Phase R) with different values of terminating resistances at node 'B'

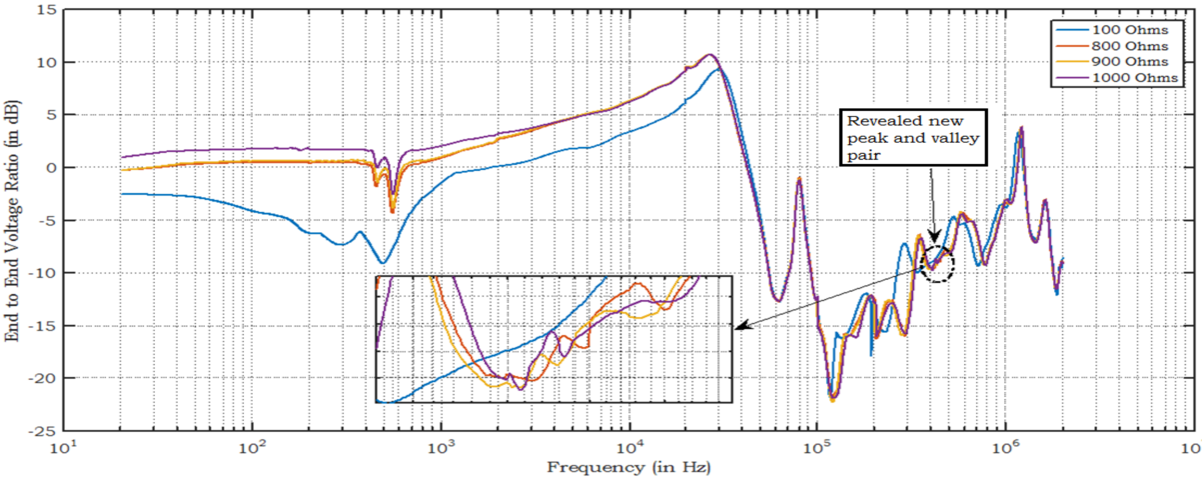

Figure 7: Frequency Response of 200 kVA transformer winding (Phase R) with different values of terminating resistances at node 'B' – reveal local peak & valley

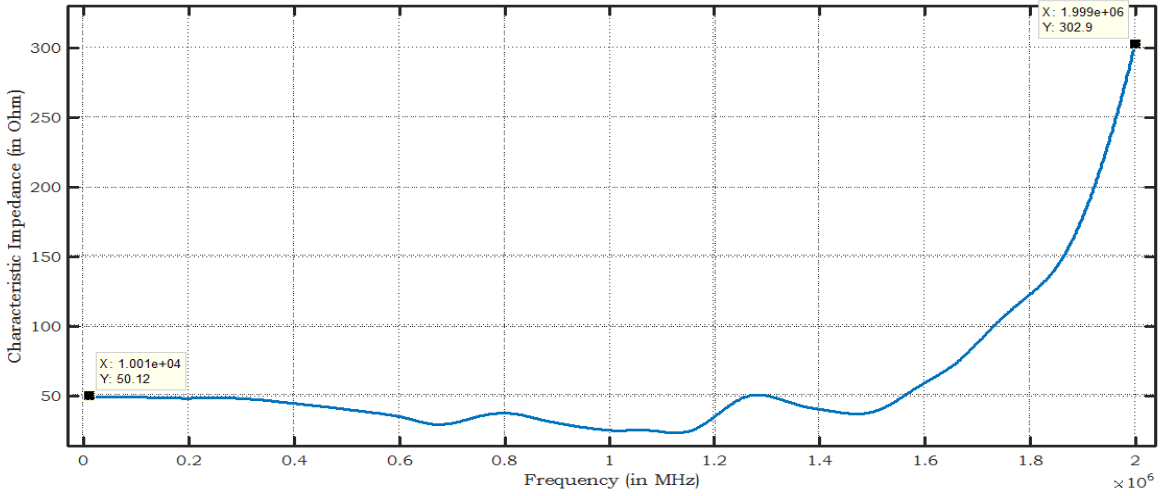

Figure 8: Variation of characteristic impedance with respect to frequency for 5 kVA transformer

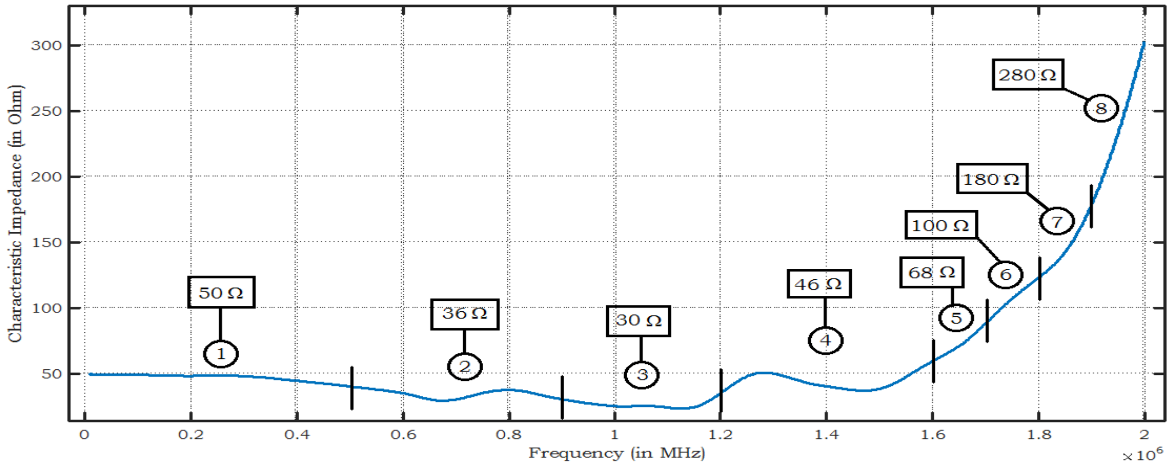

Figure 9: Terminating impedance assigned to each sub frequency band

4. EXPERIMENTAL VALIDATION

According to the fundamentals of the traveling wave, the possibilities of signal reflection arises at point ‘A’ & ‘B’ (Refer fig. 2) in the SFRA test set up. At node ‘A’, this issue can be handled by providing a resistor of 50 Ω, because the change in the characteristic impedance of coaxial cable with frequency is in-significant. It is reported in [27] that the change begins from about 1 MHz till about 50 MHz and is observed at about 7 Ω. In the SFRA test, the maximum frequency test signal used is 2 MHz. Hence the characteristic impedance of coaxial cable can be considered frequency-independent while performing the SFRA test. Node ‘B’ should be terminated by Z_t, ideally. The Z_t is a function of frequency. Hence, the value of termination provided at node ‘B’ governs the portion of the signal being reflected and refracted. To probe the effect of termination at ‘B’, frequency responses of transformer winding (R Phase, LV winding) of 5 kVA, 230 V/ 400 V and 200 kVA, 11 kV/433 V, transformers are recorded as per the instruction given in [28], provided that ‘B’ is terminated by different values of resistance. As the characteristic impedance of transformer winding generally lies around 1 kΩ, [29] therefore the value of terminating resistance at node ‘B’ is varied from 0 Ω to 1 kΩ at an interval of 100 Ω. The responses are shown in *fig. 4 to 7.*

Investigating Figs. 4 to 7 the changes observed in the frequency responses of 5 kVA & 200 kVA transformer windings, with the increase in value of terminating resistance, are as follows.

- Magnitude damping
- Shifting of response.
- Change in the magnitude of local peak and valley.
- Reveal local peak & valley.

In any circuit network, the inclusion of a resistor brings change into its response is damping, mainly. Here, this effect (damping) is reported in the low-frequency band of frequency response, significantly. The reason behind this is as follows. The phenomenon of traveling waves and the concept of characteristic impedance came into the picture if the electrical length of the network is quite long as compared to the wavelength of an applied electrical signal. The signal used in the test is the sweep frequency signal. The frequency sweep occurs over a wide band. In the low-frequency band, the electrical length of the transformer winding may be less than the wavelength of an applied electrical signal. Therefore, the additional resistors introduced in the test setup serves as damping agent rather than terminating resistors. As an effect of which magnitude damping is seen in the low-frequency response. The changes, other than magnitude damping, are seen in the middle and high-frequency band that seems to correct the frequency response. The local peak and valley divulged, may contribute to the diagnosis of winding deformation. The terminations report adverse effects (damping) on frequency response in the low-frequency band (up to 10 kHz), on the contrary, it aids to the frequency response in the middle (10 kHz to 1 MHz) and the high-frequency band (beyond 1 MHz). It is found advantageous to terminate transformer winding terminals while performing the SFRA test, for the frequency response in the middle and high-frequency band (beyond 10 kHz).

The difference, noticed in the frequency responses with the termination at point ‘B’ (refer *figure 2*) other than 50 Ω are not negligible. It seems by changing the termination at point ‘B’, the portion of the frequency response – which was hidden in the same with conventional termination, is getting revealed. This can be considered as – by tuning the termination at point ‘B’, one can have the correct frequency response of the winding, which may not in the case of test cable termination at point ‘B’ by 50 Ω.

5. SELECTION OF TERMINATING IMPEDANCE

It is marked that the variation in the value of the resistance connected at ‘B’ brings a significant change in the frequency response. This is due to the mismatch of the characteristic impedance of the co-axial cable and that of transformer winding. To match impedances, it is required to terminate node ‘B’ by the value of impedance equal to the characteristic impedance of transformer winding (Z_t). Z_t has a monotonic relationship with frequency [30]. The characteristic impedance of transformer winding can be computed using *equation (1)* if the design parameters & physical dimensions of transformer winding and core are known, [30].

$$Z_t = 120\pi\sqrt{\frac{\mu}{\epsilon}}\frac{N}{h}\frac{b}{\left\{1+\left(\frac{b}{d}\right)\right\}} \tag{1}$$

Where,
μ = magnetic permeability of electrical winding material
ε = dielectric constant of insulation material
N = total number of turns of electrical winding
h = axial length of the electrical winding
b = insulating distance between the electrical winding and transformer core
d = insulating distance between electrical winding & tank of transformer

Additionally, [31] has proposed equations to enumerate characteristic impedance of transformer winding for middle and high-frequency band (*equation 2 & 3*), as a function of winding leakage inductance (L), series capacitance (C_s) and shunt capacitance (C_g).

$$Z_t = \sqrt{\frac{L}{C_g(1-LC_s\omega^2)}} \tag{2}$$

$$Z_t = \frac{1}{j\omega}\sqrt{\frac{1}{C_gC_s}} \tag{3}$$

Z_t varies widely with frequency [32]. It is impractical to continuously tune termination at node ‘B’ with that of Z_t. Instead, it is more proper to divide the frequency range (10 kHz to 2 MHz) into a few subdivisions and each subdivision is assigned a value of terminating impedance. For this ‘Reflection coefficient’ is used as a barometer. This process is demonstrated on a 5 kVA transformer. The characteristic impedance of the 5 kVA transformer is obtained as per the instructions given in [32]. The variation of the characteristic impedance as frequency is shown in *fig. 8*. The frequency band can be seen as 8 sub-bands, each is assigned a suitable value of terminating impedance, so that the reflection coefficient lies between ± 0.1 throughout the band, refer *fig.9*.

The other side of the coin is that one needs to perform the above practice separately for every serving transformer. The reason behind this is: every transformer proposes a different characteristic impedance plot due to their different size. Hence, it is difficult to publish frequency sub-divisions and their assigned value of terminating impedances that can be applied to the entire range of power transformers, commonly.

6. CONCLUSION

In the SFRA test transformer winding is subjected to a wide frequency band. The coaxial cable and transformer winding become transmission mediums for high-frequency test signals. It is required to terminate coaxial cable at winding terminals. After going through the test connections, followed in practice, it is observed that co-axial cables, used for test connections, are properly terminated at SFRA instrument, while the ends toward transformer winding terminals (tagged by ‘A’ & ‘B’ in this paper) are left unattended. The experimental results recorded on 5 kVA & 200 kVA transformers favor termination of nodes ‘A’ & ‘B’. The impedance matching damps low-frequency response, on the other end it is correcting frequency response beyond 10 kHz. Ideally, the termination at node ‘B’ should be tuned to the value equal to the characteristic impedance of winding, continuously, but it is impracticable. It is advised to decide few values of terminating resistance within frequency band 10 kHz to 2 MHz, which is looked after by reflection co-efficient. By the proposed method of performing the SFRA test the advantage of “less time requirement for the performance in the conventional way” may getting lost. This opens the door of continuing this research work in future.

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