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A Linear Feature for On-line Monitoring of Mechanical Defects in Transformer Windings

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Abstract

Frequency Response Analysis (FRA) is mostly utilized as an effective diagnosis and monitoring tool to detect typical mechanical defects, i.e., radial deformation and axial displacement, in power transformers. However, it is an off-line technique, i.e., the transformer should be out of service or disconnected to conduct the tests. This paper presents a novel on-line method based on the measurement of terminal current and voltage signals at the power frequency to distinguish between axial displacements and radial deformations in transformer windings. To demonstrate the feasibility of this method, an appropriate detailed RLCM model of the transformer winding is used and various defects are analyzed. The simulation results show the sensitivity and capability of the proposed technique for determining the extent and type of mechanical defects in power transformer windings. Furthermore, it is a straightforward technique applying the measured signals obtained from the existing metering equipments accessible in every substation and connected to power transformer and also the results can be interpreted by non-expert staff.

Keywords: Axial displacement, condition monitoring, fault detection, mechanical faults, radial deformation, transformer windings.

Introduction

Power transformers are the most expensive and strategic apparatus in power systems. Their reliable and correct functioning is necessary for accurate operation of the whole system. High short-circuit currents and improper transportation can cause mechanical displacements of power transformer windings. The windings of transformers may be damaged more seriously in the case of the insulation deterioration or winding collapse resulting in their physical deformation. It is therefore critical to exactly monitor their in-service behavior and detect mechanical defects quickly in order to avoid catastrophic failures and costly outages. Frequency Response Analysis (FRA) as one of the well-known diagnosis and monitoring techniques has been widely used as a reliable method to detect transformer winding displacement or deformation[1-7]. FRA is based on the fact that each transformer has a unique characteristic observable in its sole frequency response. Failure detection by using this technique is mostly based on the graphical comparison of curves obtained when plotting the measured responses in various stages of the transformer life cycle. Nevertheless, detection and localization of defect cannot be assessed with the degree of precision needed for diagnosis and decision making and there is no general consensus about the interpretation of the FRA results. To solve this task several researchers suggest using a transformer model to interpret the FRA curves. Each winding can be modeled based on an equivalent electrical circuit including capacitances, resistances, self and mutual inductances. These elements are derived from the geometrical specifications of the transformer windings, core, tank, etc. This electric model determines the features of FRA consisting resonances and anti-resonances. The mechanical defects, i.e., Radial Deformations (RD) and Axial Displacements (AD) change these parameters and as a result, deviations in the frequency response spectrum of windings.

The Low Voltage Impulse (LVI) and Sweep Frequency Response Analysis (SFRA) are two techniques, which are typically used to carry out the FRA measurements. Impedance (U_{in}/I_{out}) and voltage ratio (U_{out}/U_{in}) transfer functions are two possibilities of FRA measurements. The FRA is assessed by comparison of healthy and faulted measurements. There are many comparative algorithms that have been proposed by researchers to detect the fault type in transformer windings. The artificial intelligence methods[8-10], numerical techniques[11-14], estimation methods[15,16] and equivalent circuit models[17,18] are four major algorithms.

Despite useful performances of FRA, this method has some main drawbacks. It is in practice an off-line technique and it is very sensitive to the measuring setups like measuring connections and cables in higher frequency ranges[19]. Hence, providing an alternative online method to detect winding mechanical defects is desirable. In this regard, various methods have been employed for online evaluation of transformer winding mechanical defects[20].

Since short circuit impedance of the transformer is related to the winding configuration and physical dimensions, it has been introduced as a method to judge the status of the transformer winding. Detecting the winding deformation of the power transformer using online calculations of the short circuit reactance has been proposed[21-24]. Nevertheless, a number of researchers have undoubtedly discussed the accuracy of this method[1,20].

Rybel[25] proposed to inject a pulse signal to the bushing tap of a power transformer as an online condition monitoring technique. The high voltage bushing taps are used as a voltage divider and have the potential to measure the input voltage about 2 MHz. It may still work at higher frequency, but it will not be linear[26]. Practical works and simulations show that in the low frequency range, the bushing does not affect transformer signature but has a significant impact on FRA results at higher frequencies[25,26]. A new technique for on-line detection of the Short-Circuit (SC) faults of the transformer based on FRA is proposed[27,28]. However, the detection of the fault location along the winding was not under consideration. In these studies, only different values of resistance have been embedded in the winding to make electrical faults. A bibliographic review and analysis of online application of FRA technique and advances have been obtained in this field to monitor the transformer in real time is presented[29]. This paper addresses the current status and future trends that can be useful for following research in this area.

The application of the negative sequence components of the primary and secondary line currents for online detection of SC fault has been another technique proposed but without considering mechanical defects[30]. SC location diagnosis in transformer based on two low frequencies waveforms is proposed by Hocine and et al[31]. This fault can be detected by the propagation of two waves generated by the two inverters with low and different frequencies. This method is independent of the system frequency, without any comparison to a reference signal.

Furthermore, an online technique to detect the internal faults is proposed based on the construction of the voltage-current locus diagram that is considered as the fingerprint for the transformer under study[32].

Ultra-Wideband (UWB) sensors have been proposed to detect RD extent through on-line monitoring of transformer winding[33]. Furthermore, UWB sensors have been suggested to detect AD extent[34]. The UWB technique is just in the research phase and the results are not obtained from a real winding. Of course, it is possible to increase the accuracy and precision of the detection through a hybrid technique based on UWB sensors and on-line FRA analysis.

Using the tank vibration diagnosis method to monitor the state of the inner parts of transformer that are covered by transformer tank has been proposed by García and et al[35-39]. Any repetitive movement in transformer core or winding lead to the change of transformer vibration response. It can be potential indicators of a change in transformer geometry. It has been suggested to be considered as an online method to detect the winding deformation in power transformers.

Current Deviation Coefficient (CDC) as an effective indicator for detecting winding deformation and its extent has been introduced by Joshi and et al[40]. In this method, a high frequency low voltage signal has been applied to the line-end of the live power transformer and high frequency components of the terminal currents have been continuously measured. Any deviations of these currents from their fingerprint values have been used for online deformation diagnostics.

The recently developed characteristic impedance method, has been proposed as an alternative of FRA[41]. The wavelet coherence technique has been proposed by Ghanizadeh and Gharehpetian, for the comparison between two characteristic impedance signatures and detection of AD and RD faults and discrimination between them. This method can effectively be used in an online scheme for assessing the condition of the transformer winding in the future[42].

The fault diagnosis process consists of two stages, i.e., feature extraction and classification stages. Feature extraction is a type of data preprocessing that transforms a pattern from its original form into a new proper form dominating some features which represent the information content of an observation. If suitable feature is selected for a problem, the pattern recognition will be performed more effectively. The selection of linear features with different ranges for different faults can remove the classification stage and the decisions can be made directly with fewer mistakes by operators[43]. Suppose that there exists only AD or RD in the transformer winding. There are various classification methods, to classify the transformer test results in one of the AD or RD classes. By considering well separability of these classes of defects, it can be argued that there is no need to use complex classification procedures to relate an unknown test result to one of these classes.

However, different authors unanimously mentioned that this topic is still required to have a reliable online diagnosis system[29]. As an extension of previous research, this paper introduces a new online technique to detect AD and RD defects in transformer winding. Unlike FRA, which uses a sweep frequency in the range of some MHz, this technique is based on a single frequency measurement, e.g. at power frequency.

Actually, the novelty of this paper is the application of any arbitrary three current and/or voltage signals that are measured from transformer terminals in power frequency range for detection of mechanical defects in transformer winding. For this purpose, a linear feature considered as the fingerprint of the transformer is proposed. In other words, the proposed algorithm that has been presented for the first time by the authors is relying on constructing a line relating to these signals. These signals can be obtained by typical metering equipments attached to any power transformer and there is no need to additional equipment. Since the obtained feature is linear, therefore its interpretation for the detection of faults is so easy and can be made directly with fewer mistakes by the operator. In other words; there is no need to expert personnel. The feasibility of the proposed method is demonstrated for a 10/0.4 kV, 1.2MVA transformer winding.

Modeling of Winding and Mechanical Defects

Detailed RLCM Model: A lumped-parameter equivalent circuit model is utilized in this paper in order to study the correlation between the winding mechanical defects and their effects on the proposed feature obtained from voltage and current signals. This model is authentic for a wide frequency range up to a few MHz[3]. This model is used for a 10/0.4 kV, 1.2MVA single phase transformer with inverted high voltage (HV) winding including 30 double discs, 11 turns in each disc and a layer-type low voltage (LV) winding. One section of the detailed RLCM model is illustrated in figure-1. This figure shows i-th section of HV winding and j-th section of LV winding, where contains parallel capacitance of each section (K_p), earth capacitance (C_e), capacitance between LV and HV windings (C_{HL}), self-inductance (L), mutual inductance (M), series resistance representing conductor resistance of each section (R_s), shunt resistance that represents dielectric losses (R_p) and insulation resistance between each section and earth (tank or core). The analytical equations for the calculation of all mentioned parameters have been presented by Rahimpour[3], Bjerkan[44] and Gharehpetian[45].

Winding Defects: The most common reason of mechanical defects in transformer windings is the short circuit current. Any variation in the physical conditions of windings can result in variations in parameters of the detailed model. In this paper, AD and RD are studied as two major types of mechanical defects and they should be modeled in the detailed model. The location of RD is generally in the outer HV winding. It is shown that the variations of inductances due to RD defects are negligible compared to changes in the values of ground capacitances[3]. Figure 2 demonstrates four types of RD. These defects are applied to the detailed model by the following equation in order to model the forced buckling[44]:

$$r(\theta) = \begin{cases} r_0 + \dfrac{d}{2}(\cos(s\theta) - 1) & for \quad 0 \le \theta \le \dfrac{2\pi}{s} \\ r_0 & otherwise \end{cases} \qquad (1)$$

Where, d is the deformation depth, s is the deformation span width and θ is the angle. R and r_0 are also the radius of radial deformed and non-deformed segments, respectively. The ground capacitance between the HV winding and transformer tank can be obtained as follows[44]:

$$Ce_i = \sum_{\theta=0}^{2\pi} \left(\frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(r_0/r(\theta)\right)} \right) .\Delta\theta \qquad (2)$$

Where, $\Delta\theta$ is the fraction of the perimeter under investigation, ε_r and ε_0 are relative permeability and permittivity of the free space, respectively. The relative variation in the distance between HV winding and tank affects the ground capacitance value.

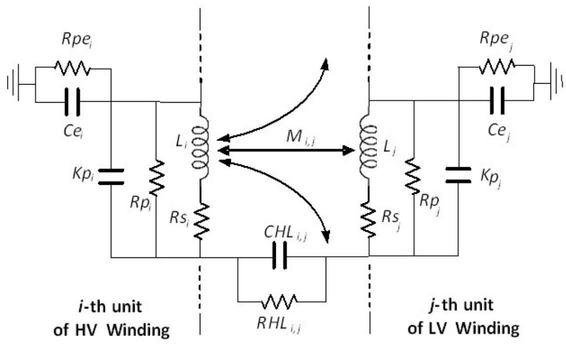

Figure-1
Detailed RLCM model of two winding transformer

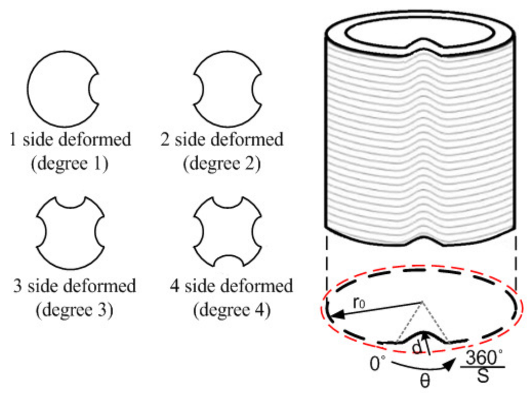

Figure-2
Typical radial deformations

Unlike RD, AD defects are axial movements of the HV winding from the foreside of the LV winding, as depicted in Figure 3. Through the calculations, it has been shown that these defects predominantly affect the mutual inductances between two windings and variations of capacitances can be neglected[3]. The self and mutual inductance can be calculated based on the equations obtained from the third and fourth Maxwell's equations or vector potential method[3,44].

Proposed Technique: The proposed technique relies on constructing a diagram locus relating to three signals obtained from measurements on transformer terminals. In this method, two fractions are calculated. One signal is assumed as the denominator, while two other signals are the nominator of their fractions.

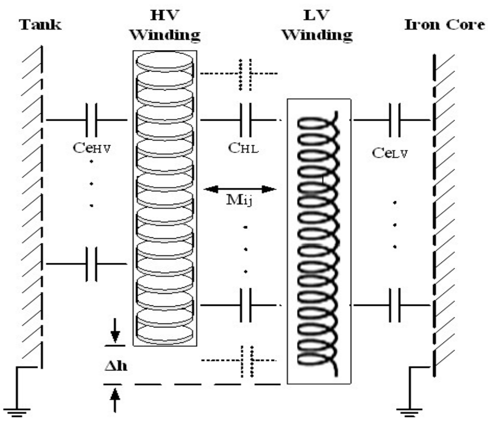

Figure-3
Axial displacement in transformer winding

To construct this diagram, one fraction is displayed on *x*-axis and the other one is placed on *y*-axis. The signals are sinusoidal signals with a difference in their phase angle. The idea of the application of power frequency sinusoidal signals has been proposed by Abu-Siada and Islam[32]. In that paper, the signals have been obtained from a classical model of the single-phase transformer. In this paper, the same model is used.

Assume that *f*, *g* and *h* are three periodic functions with the same frequency.

Therefore, Let,

$$x(t) = \frac{f(t)}{h(t)} \quad and \quad y(t) = \frac{g(t)}{h(t)} \tag{3}$$

Suppose that, we have:

$$\begin{aligned} f(t) &= A\sin(\omega t + \alpha) \\ g(t) &= B\sin(\omega t + \beta) \\ h(t) &= C\sin(\omega t + \gamma) \end{aligned} \tag{4}$$

Where *α*, *β* and *γ* are constant numbers. *x(t)* can be written in the following form:

$$\begin{aligned} x(t) &= \frac{f(t)}{h(t)} = \frac{A\sin(\omega t + \alpha)}{C\sin(\omega t + \gamma)} = \frac{A\sin(\omega t + \gamma - \gamma + \alpha)}{C\sin(\omega t + \gamma)} \\ &= \frac{A[\sin(\omega t + \gamma)\cos(\alpha - \gamma) + \cos(\omega t + \gamma)\sin(\alpha - \gamma)]}{C\sin(\omega t + \gamma)} \\ &= \frac{A}{C}[\cos(\alpha - \gamma) + \sin(\alpha - \gamma)\cot(\omega t + \gamma)] \end{aligned} \tag{5}$$

Similarly, for *y(t)* we have:

$$\begin{aligned} y(t) &= \frac{g(t)}{h(t)} = \frac{B\sin(\omega t + \beta)}{C\sin(\omega t + \gamma)} = \frac{B\sin(\omega t + \gamma - \gamma + \beta)}{C\sin(\omega t + \gamma)} \\ &= \frac{B[\sin(\omega t + \gamma)\cos(\beta - \gamma) + \cos(\omega t + \gamma)\sin(\beta - \gamma)]}{C\sin(\omega t + \gamma)} \\ &= \frac{B}{C}[\cos(\beta - \gamma) + \sin(\beta - \gamma)\cot(\omega t + \gamma)] \end{aligned} \tag{6}$$

Eliminating $\cot(\omega t + \gamma)$ in equations (5) and (6), we have:

$$\frac{x(t) - \frac{A}{C}\cos(\alpha - \gamma)}{y(t) - \frac{B}{C}\cos(\beta - \gamma)} = \frac{A\sin(\alpha - \gamma)}{B\sin(\beta - \gamma)} \tag{7}$$

This equation shows a simple linear relation between *x(t)* and *y(t)* which can be represented by a line (i.e., y=mx+b) and is valid for any moment of time. The constants *α*, *β* and *γ* determine the situation and the slope of the line in the plane.

It should be noted that the most important property of these functions is that they have the same frequency. Moreover, it should be mentioned that there is no limitation in the signal type, i.e., they can be either current or voltage signals measured from HV and/or LV terminals of the transformer. Whereas the proposed technique by Abu-Siada and Islam relies on constructing a locus diagram of the input and output voltage difference of a particular transformer winding on the *y*-axis and the winding input current on the *x*-axis. This is the most important advantage of the proposed method in comparison with the method presented in previous studies.

The transformer can be analyzed by the line equation, i.e., the line slope and the intersection point between the line and *y*-axis.

In this paper, the signals under study *f*, *g* and *h* are selected as the terminal voltage of HV and LV windings and the earth current of the HV winding, respectively, i.e.:

$$\begin{aligned} f(t) &= u_1(t) = U_{m1}\sin(\omega t + \alpha) \\ g(t) &= u_2(t) = U_{m2}\sin(\omega t + \beta) \\ h(t) &= i_1(t) = I_{m1}\sin(\omega t + \gamma) \end{aligned} \tag{8}$$

and the *x*-axis and *y*-axis are considered as Z_1 and Z_2, as follows:

$$Z_1 = x(t) = \frac{u_1(t)}{i_1(t)} \quad and \quad Z_2 = y(t) = \frac{u_2(t)}{i_1(t)} \tag{9}$$

Considering the equation-7, the Cartesian relation between Z_1 and Z_2 represents a line at any moment of time. So, the proposed linear feature is easy to implement and suitable to analyze for fault detection in power transformer winding.

Results and Discussion

Simulation Results: For simulation and applying the proposed technique, the test object of Rahimpour's study is applied[3]. This test object is the HV homogeneous winding of a 10/0.4 kV, 1.2 MVA power transformer with 60 discs, 11 turns in each disc and a layer-type LV winding. The dimensions of LV and HV conductor winding are 11mm ×4mm and 9mm×2.5 mm, respectively. The thickness of the winding paper is 0.2mm. Figure 4 shows the dimensions of this transformer. The HV terminal is grounded and the LV winding is neutral floating in the test set-up. The input signal is applied to the HV winding and then the HV winding earth current and obtained voltages from the HV and LV winding are recorded.

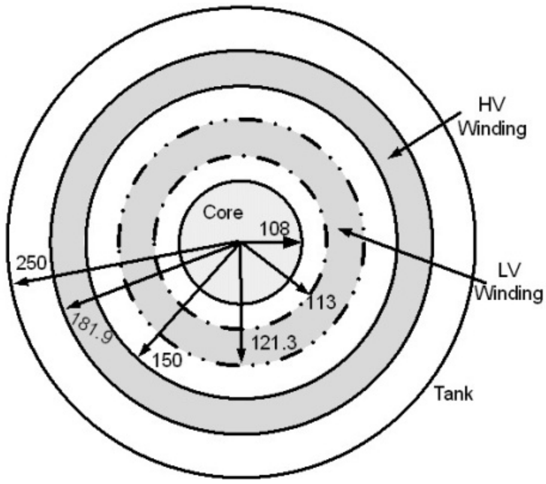

Figure-4
Dimension of test object [mm]

Four deformation degrees shown in figure-2 are modeled as RD. It is assumed that each three adjacent double-discs of the HV winding are deformed for each case. Thus, the winding is divided into ten equal sections and for each section; four degrees of deformation are considered. The depth of the deformation is assumed d=10% of the radius. The values of the ground capacitance between each disc and the transformer tank in healthy and defected conditions are listed in Table 1. Also, in order to study the sensitivity of the proposed technique for AD, the HV winding has been moved upward in 16 steps, i.e., 5 mm at each step. The total displacement is considered to be equal to 10 percent of the total winding height. Some of values of the inductances for normal and defected modes from three sections of the winding are given in table-2. These sections are in line-end section, midsection and earth-end section.

The baseline fingerprint of this technique is shown in figure-5. The equation of this line is obtained as follows:

$$Z_2 = -0.03596089\, Z_1 + 0.02363352 \qquad (10)$$

According to the proposed technique, if any defect occurs in the winding, the line slope and the intersection point between the line and *y*-axis will change.

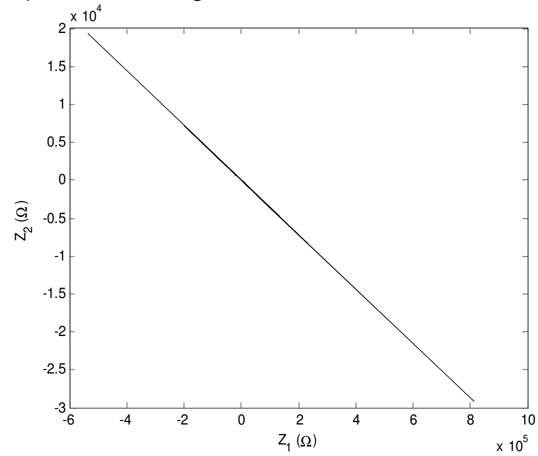

Figure-5
Determined line for normal mode

The characteristics of lines for different cases of RD defects from 1-side to 4-side in different locations along the winding are listed in table-3. In other words, as depicted in figure-6, it can be observed that the line slope is -0.035967 for 1-side, -0.035983 for 2-side and -0.035997 and -0.036 for 3-side and 4-side deformations, respectively. An ascendant trend for the intersection points between the lines and *y*-axis in the range of 0.02364 up to 0.02372 can be observed. Moreover, it can be used to detect the location of RD defects. For example, the variation of line slope for 1-side RD is shown in figure-7.

Table-1
Value of CeHV in normal and deformed cases

	Normal Winding	1 side Deformed	2side Deformed	3 side Deformed	4 side Deformed
CeHV (pF)	2.7921	2.7228	2.6639	2.5998	2.5356

Table-2
Mutual inductances for normal and AD defects

	$M_{HV,LV}$ (μH)	Normal Winding	20mm	40mm	60mm	80mm
Line-end section	$M_{30,5}$	3.87	3.76	3.65	3.55	3.46
	$M_{30,10}$	5.17	4.98	4.80	4.63	4.47
	$M_{30,15}$	7.66	7.26	6.90	6.57	6.27
	$M_{30,20}$	13.87	12.74	11.75	10.89	10.14
Mid-section	$M_{15,5}$	9.61	9.00	8.47	7.99	7.56
	$M_{15,10}$	20.01	18.07	16.34	14.85	13.57
	$M_{15,15}$	13.82	15.14	16.68	18.46	20.42
	$M_{15,20}$	7.64	8.09	8.57	9.12	9.74
Earth-end section	$M_{5,5}$	18.84	20.82	22.59	23.33	22.51
	$M_{5,10}$	9.24	9.87	10.59	11.40	12.33
	$M_{5,15}$	5.89	6.15	6.45	6.76	7.11
	$M_{5,20}$	4.27	4.41	4.57	4.73	4.90

In table-4, the amount of the line slope and intersection points between the line and y-axis are shown for different amounts of AD. As can be seen in the table, the range of line slope variations for these faults is in the range of -0.0339 up to -0.0358 (Figure 8). The variation of line slope for different types of faults is selected as a feature, illustrated in figures-6-8 for different types of RDs and extents of ADs, respectively. As illustrated in these figures, the variation of this feature lies totally in different intervals depending on the defect type. Thus, this feature can be used as a proper index to discriminate between two types of mechanical defects and even their location and extent in the transformer winding.

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The transformer is connected to the network through its bushings and it is just possible to obtain signal samples from them. Hence, to propose an on-line monitoring system, the bushings are modeled using a T-model presented by Wang et al[46]. This model is illustrated in Figure 9. In this section, the obtained sinusoidal signals from HV and LV bushings and the HV winding earth current, just as the previous section, are applied to the proposed technique to validate the efficiency of the proposed method. Different cases of defects are simulated and the results obtained for AD are illustrated in Table 5. As the previous cases, a regular trend can be observed in the results. The simulation results of RD defects considering the model of the bushing show the same procedure listed in table-3.

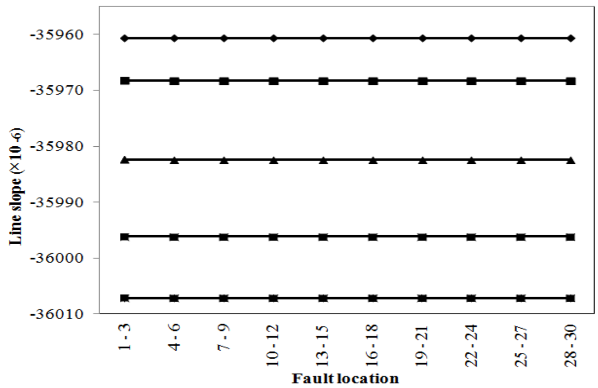

Figure-6
Variations of line slope for different types of RDs.

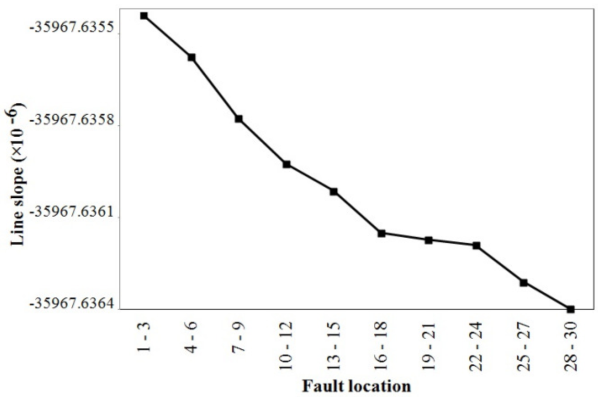

Figure-7
Variations of line slope for 1-side RD

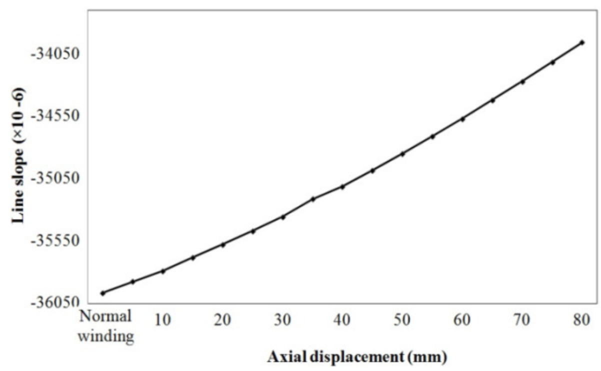

Figure-8
Variations of line slope for different ADs

Table-3
Line equation for different cases of RD along winding

	Fault location	Line slope (×10 $^{-6}$)	Intersection with y-axis (×10 $^{-6}$)
Normal winding		-35960.889562	23633.519301
One side radial deformation	1 - 3	-35967.635389	23642.451231
	4 - 6	-35967.635525	23642.653376
	7 - 9	-35967.635725	23642.851741
	10 - 12	-35967.635874	23642.919899
	13 - 15	-35967.635961	23642.998231
	16 - 18	-35967.636099	23643.336801
	19 - 21	-35967.636121	23643.509251
	22 - 24	-35967.636138	23643.617408
	25 - 27	-35967.636258	23643.758396
	28 - 30	-35967.636347	23643.847753
Two side radial deformation	1 - 3	-35983.095869	23675.175456
	4 - 6	-35983.096013	23675.384392
	7 - 9	-35983.096035	23675.588243
	10 - 12	-35983.096187	23675.762659
	13 - 15	-35983.096247	23675.876349
	16 - 18	-35983.096343	23675.899128
	19 - 21	-35983.096918	23675.902367
	22 - 24	-35983.097019	23675.988947
	25 - 27	-35983.097285	23676.027327
	28 - 30	-35983.097757	23676.153369
Three side Radial deformation	1 - 3	-35997.123043	23685.203357
	4 - 6	-35997.123133	23685.333106
	7 - 9	-35997.123509	23685.888832
	10 - 12	-35997.123613	23685.994229
	13 - 15	-35997.123896	23686.202409
	16 - 18	-35997.123920	23686.521734
	19 - 21	-35997.123991	23686.667693
	22 - 24	-35997.124002	23686.798815
	25 - 27	-35997.124329	23686.918697
	28 - 30	-35997.124380	23687.097871
Four side radial deformation	1 - 3	-36007.101097	23726.465766
	4 - 6	-36007.101218	23726.650056
	7 - 9	-36007.101600	23726.818208
	10 - 12	-36007.102913	23727.050229
	13 - 15	-36007.102873	23727.187774
	16 - 18	-36007.103086	23727.376726
	19 - 21	-36007.103223	23727.545376
	22 - 24	-36007.103319	23727.656580
	25 - 27	-36007.103445	23727.794915
	28 - 30	-36007.103525	23727.839939

Use of the transient signals generated by system switching operations and lightning was a procedure proposed to determine mechanical defects in the transformer windings in real time[27]. The proposed method can be applied to transient signals as well. Using the Fast Fourier Transform (FFT), the signal can be written in the form of summation of sinusoids signals. One of these signals, i.e. only an arbitrary one at an arbitrary frequency, can be selected and the proposed method can be applied to this signal. In addition, alternative mathematical solutions such as wavelet transform exist for signal filtering and processing. It may be a remarkable option due to its multi-resolution analysis approach.

Further studies can be carried out to develop the proposed method. First, for experimental validation of the study, practical works can be performed. Second, a real deformation, which is a combination of axial and radial deformations, such as hoop buckling, stretching, tilting, telescoping and etc., can be studied. Third, the integration of the proposed method and signal processing techniques can be used for detection of faults using power system transients.

Table-4
Line equation for different extents of AD

Fault extent	Line slope (×10^{-6})	Intersection with *y*-axis (×10^{-6})
Normal winding	-35960.889562	23633.519301
AD05	-35871.689871	23534.333135
AD10	-35786.234567	23444.014618
AD15	-35678.449870	23334.014602
AD20	-35574.371885	23196.871241
AD25	-35465.292133	23074.213175
AD30	-35351.069689	22957.909848
AD35	-35210.783901	22848.296253
AD40	-35107.973608	22691.066390
AD45	-34978.975523	22536.076268
AD50	-34845.513309	22396.119501
AD55	-34707.408774	22226.597855
AD60	-34564.867102	22063.160546
AD65	-34418.262119	21914.018157
AD70	-34267.528501	21738.721250
AD75	-34112.865957	21567.087149
AD80	-33954.722234	21395.147466

Table-5
Line equation for different extents of AD with bushing model

Fault extent	Line slope (×10^{-6})	Intersection with *y*-axis (×10^{-6})
Normal winding	-35959.253843	38015.346744
AD05	-35870.058367	37880.488235
AD10	-35784.956985	37738.719116
AD15	-35676.831031	37602.888566
AD20	-35572.752766	37424.111028
AD25	-35463.677846	37257.836843
AD30	-35349.463388	37095.851887
AD35	-35209.472902	36846.239543
AD40	-35106.379632	36731.789572
AD45	-34977.384849	36525.212830
AD50	-34843.930973	36331.870391
AD55	-34705.829100	36107.116997
AD60	-34563.292973	35886.684218
AD65	-34416.698274	35678.909040
AD70	-34265.969911	35443.329090
AD75	-34111.314751	35209.838466
AD80	-33953.137106	34974.633524

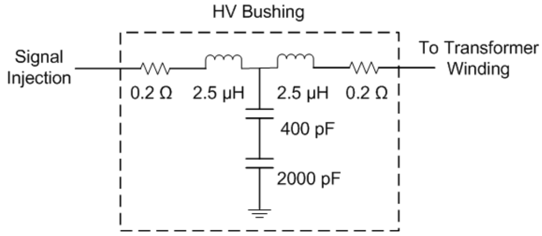

Figure-9
Bushing model

Conclusion

In this study, a linear feature for the detection of RD and AD defects in transformer winding has been proposed. Thorough the proposed technique, a line characteristic has been obtained which can be used as the fingerprint of the transformer. Any defect can change this characteristic. The simulation results show that the proposed feature is able to discriminate between mechanical defects completely. The obtained results can be easily used for the interpretation of results; in comparison with FRA method. The signals applied to this technique can be chosen from a wide range of voltage or current signals of HV and LV windings at power frequency without any effect on the accuracy of the proposed feature. Since the proposed technique is applicable at power frequency, it is suitable for online monitoring of transformers without using any additional measurement device. Moreover, the proposed technique is tested on the signals obtained from the bushings.

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