Transformer inter-turn failure detection based on leakage flux and vibration analysis

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Abstract
Inter-turn winding fault is one of the most critical failures of the transformers. Here, a comprehensive transformer leakage flux analysis under inter-turn winding fault is presented, and the feasibility and sensitivity of leakage flux-based fault detection methods are investigated. The leakage flux fault detection strategies are classified into vibration-based methods and search coil-based methods. Flux leakage-based methods have been studied and compared. Moreover, the effects of various important factors, such as fault severity, fault location, load power factor, and loading rate in transformer under inter-turn faults are studied. Furthermore, two new online methods based on leakage flux and vibration analysis are proposed. In the first method, search coils voltage analysis is used for fault detection. In the second one, the vibration of the transformer is measured using the Digital Accelerometer (ADXL) sensor and compared with the vibration of the normal conditions, and based on the amount of vibration, fault detection is performed. The simulation and experimentation results on 20/0.4 kV, 50 kVA distribution transformer demonstrated that the implementation of leakage flux-based methods provides valuable information on the transformer behaviour, which can be used to detect transformer winding faults.

1 | INTRODUCTION

Power transformers are one of the most crucial and expensive devices in the power system. A significant reason for transformer failure and unexpected outages are inter-turn winding faults. Studies demonstrate that 70%–80% of the power transformer damages arise from internal faults [1]. At the low current side, inter-turn faults detection is a critical issue that has been surveyed in various research [2–5]. The incidence percentage of different fault types in a transformer is shown in Figure 1. It can be seen that 30% of all faults which occurred in transformers are related to winding faults [6].

Although inter-turn faults in the initial state do not bring about significant variation in the transformer's performance, the circulation current in the shortened turns increases gradually [7]. These currents produce local heat that causes more destruction on the insulator; consequently, minor faults lead to more significant faults such as phase to phase faults or high voltage (HV) to low voltage (LV) faults [8]. Initial detection of the inter-turn fault in power transformers is essential due to high cost and regular maintenance. This situation becomes critical whenever transformers are nearing the end of their lifetime in which fault is more expected [9].

In the literature, various methods are proposed for transformer fault detection. Differential protection, dissolved gas analysis (DGA), wavelet transform, neural network, flux-based method, terminal current, and frequency response analysis (FRA) are the proposed methods of fault detection in the transformer. In [12], the impulse frequency response approach (IFRA) was used to monitor the mechanical and inter-turn short-circuits in transformers. An experimental investigation was surveyed to analyse the effect of loads on this diagnosis method. An experimental study was exerted to examine the ability of IFRA to investigate inter-turn short-circuits inside transformers under various load conditions. Examinations on the two transformer sections proved that the inter-turn short-circuit analysis in loaded transformers are plausible with the online IFRA method. However, the transformer's load changes...
the effectiveness of the online IFRA by decreasing the impulse response's spectrum. Investigation of the results has led to the following signs. Table 1 indicates various fault detection methods and has presented the advantages and disadvantages of each of them. Among the techniques reviewed in Table 1, online-based methods are more exerted. Although most methods have online capability detection, the method’s complexity and precision should also be considered.

Leakage flux-based methods have been investigated in [7, 8, 10, 11]. In [7], the leakage flux application was utilised to deal with the online detection of inter-turn faults in power transformers. In [8], the transformer state and fault location are analysed by utilising the transformer leakage flux. In the proposed method, the fast Fourier transform (FFT) is applied to search coils to extract features of transformer leakage flux, and the obtained features are sorted out by the probabilistic neural network. To reduce data dimensions, principal component analysis is applied; consequently, the structure of the probabilistic neural network for fault diagnosis is improved. In [10], a novel leakage flux sensor is introduced, and a flux-based method is recommended to identify and distinguish the faulty phase in transformers to utilise in online states. In the meantime, by utilising the technique, the faulty zone can be recognised in offline states. In [11], a simple, sensitive and robust linkage flux-based method is suggested to preserve the power transformers. In this way, some distant multi-turn windings as search coils have to be wrapped around the transformer core legs to sense the associated passing flux.

Here, a comprehensive transformer leakage flux analysis under inter-turn fault is presented with the aim of faults detection. The leakage flux fault detection strategies are classified into the vibration-based method (VBM) and search coil-based method (SCBM), and flux leakage-based methods; they were studied and compared. This modelling aims to achieve an

![Table 1](image)

**Table 1** Summary of inter-turn faults detection methods

| Detection methods                  | Advantages                                      | Limitations                                      | References |
|-----------------------------------|------------------------------------------------|-------------------------------------------------|------------|
| DGA                               | - Detection of any abnormality at incipient level | - Expensive                                      | [13–15]    |
|                                   | - Possible by both on-line and offline DGA      | - Ambiguous analysis                             |            |
|                                   | - Expensive                                      | - Not useful for oil-less transformer            |            |
| FRA                               | - The capacitive effect can be detected at high frequency | - This method needs previous data on the transformer | [12, 16–18]|
|                                   |                                                 | - This method needs complicated tools for detection |            |
|                                   |                                                 | - Offline method                                 |            |
|                                   |                                                 | - Needs expert's opinion and sophisticated instruments |       |
| Negative sequence                 | - The signal for fault detection is available   | - Unable to locate the fault                     | [19, 20]   |
| Partial discharge                 | - Well-established method in power utilities    | - This method is under the influence of tank and windings | [21–23]   |
| Flux-based method                 | - Precise and accurate                          | - Changes in the transformer structure           | [7, 8, 11, 24] |
|                                   | - Exact fault location detection                 | - Models developed for verification purposes     |            |
|                                   |                                                 | - Requires the details of the transformer structure |            |
| Voltage and current measurement   | - Models developed for verification purpose     | - Unable to locate the fault                     | [9, 25, 26]|
| Differential protection           | - Classical robust method                       | - Unable to detect inter-turn faults at initial levels | [27–29]   |
|                                   | - Online monitoring is possible                  | - Mainly depends on the precision of the current transformer |        |
|                                   |                                                 | - Sensitive to winding insulations breakdown     |            |
|                                   |                                                 | - Sensitive to the structure of the transformer  |            |
| Intelligent approach              | - Detect minute faults                          | - Training data required                        | [30–33]   |
|                                   | - Robust against missing data                   | - The problem of local minima, memory, and computations |           |
| Vibration analysis                | - This method can detect mechanical and electrical fault | - Vibration model is complicated                  | [34–36]   |
| Other methods (Park's transform, symmetrical components) | - Detect faults by measuring phase current | - The sensor must be mounted on the winding |            |
|                                   | - Online detection is possible                   | - Computations and response time is also prolonged in certain cases of fault detection. | [34, 35]   |

Abbreviations: DGA, dissolved gas analysis; FRA, frequency response analysis.
accurate investigation of faulty transformer performance and
surveying the possibility of using leakage flux variations for fast
detection of inter-turn faults in the transformer. Moreover, the
feasibility and sensitivity of fault detection methods based on
flux leakage analysis are presented. The contributions of this
study can be listed as below:

1. Transformer inter-turns fault precise modelling and leakage
   fluxes analysis under various faults conditions is investigated.
2. Feasibility and sensitivity of fault detection methods based
   on flux leakage analysis are presented.
3. Investigation of the effect of leakage flux on the trans-
   former and possible use for turn-to-turn fault detection.
4. A new SCBM is proposed.
5. A new online method based on vibration signature analysis
   is proposed.

This article is organised as follows. In Section 2, transformer
modelling using the FEM method is presented to model the transformer’s behaviour. Section 3 introduces the transformer’s behaviour analysis under inter-turn faults. In Section 4, the simulation and experimental results are discussed. In Section 5, proposed fault detection methods are discussed, and final remarks are presented in Section 6. Finally, the study is concluded in Section 7.

2 | TRANSFORMER MODELLING USING FEM

To model the transformer behaviour accurately, a two-
dimensional (2D) FEM simulation is utilised. Furthermore, the
transformer electrical and magnetic parameters are obtained
from the real transformer in the laboratory. Exact details of the
under-survey transformer are given in Table 2. Maxwell software
is utilised to model the transformer fault accurately. The
transformer and coils structure are modelled to investigate the inter-
turn fault, as shown in Figure 2. Modelling of the internal fault on
HV winding in Figure 2c and limiting the fault resistance (Rf) is
utilised to initiate the fault on the winding. The fault resistance
models the resistive part of the dielectric material in the equiv-
alent parallel circuit model of the shortened turns. Furthermore,
the fault severity depends on fault impedance and the number of
shortened turns. Therefore, with the transformer’s developed
FEM model, internal winding faults can be simulated at different
parts of LV and HV windings with different levels of severity.

To simulate the transformer accurately, a mesh that pro-
duces second-order triangle components is adapted to simulate
the core, windings and insulator space between windings and
borders. First, to obtain different values in a faulty transformer,
a potential magnetic vector in core and winding is computed in
each mesh using Equation (1), then other values, such as
current, voltage, and so on, are computed.

\[
\nabla \times \left( \frac{1}{\mu} \nabla \times A \right) + \sigma \left( \frac{\partial A}{\partial t} + \nabla V \right) = J_s \tag{1}
\]

where \(A\), \(J_s\), \(\mu\), and \(\sigma\) are the potential magnetic vector, current
density, magnetic permeability, and electrical conductance,
respectively. Moreover, flux density is also given by Equation (2):

\[
B = \nabla \times A \tag{2}
\]

where \(A\) is the magnetic field amplitude.

3 | TRANSFORMER BEHAVIOUR ANALYSIS UNDER INTER-TURN FAULTS

In this section, transformer behaviour investigation under
healthy and fault conditions is presented. A healthy trans-
former state has been illustrated in Figure 3, magnetic flux lines

| Table 2 | The exact detail of the understudy transformer |
|-----------------|-----------------|
| Quantity | Value |
| Primary voltage | 20 kV |
| Secondary voltage | 0.4 kV |
| Rated power | 50 kVA |
| Number of primary winding turns | 4155 |
| Primary winding resistance | 100 \(\Omega\) |
| Number of secondary winding turns | 96 |
| Secondary winding resistance | 0.0089 \(\Omega\) |
| Width of window | 292 mm |
| Height of HV winding | 225 mm |
| Height of LV winding | 287 mm |
| Primary and secondary connection | Y/Z (zigzag) |
| Cooling method | ONAN |
| Voltage regulation | 4% |

Abbreviations: LV, low voltage; HV, high voltage
cross the space between windings vertically with zero distortions, so if the horizontal line which passes through the middle of the transformer is assumed as the reference axial, flux lines are exactly symmetric based on this line alignment. In Figure 4, asymmetry in the distribution of magnetic flux lines under inter-turn faults is due to the increment of leakage flux and its radial component in the linkage coils environment. In a healthy state, the transformer’s leakage flux has a minor contribution to form the total linkage flux, and flux lines flow axially by passing through the space between the transformer’s windings. Faraday’s law states that the electromotive force which exists in a coil is proportional to the electromagnetic flux variation, so for constant frequencies, the amount of electromagnetic flux that enters the coil depends on the induced electromotive force in the coil terminals. Thus, the more the assumed coil is shortened, the more the coil voltage is reduced and circulating current appears in coil restricting the flux entering the coil. Lenz’s law asserts that the induced current in the linkage coil is directed to resist the change in flux and uses a mechanical force resisting the movement due to a change or a movement in the magnetic field. Here, a survey has been investigated based on the ideal state when a coil with complete conductivity is shortened through zero fault resistance so that the coil terminals voltage would be zero, and there is no flux flow in the

**FIGURE 3** Flux density lines for a healthy state

**FIGURE 4** Flux density lines for inter-turn faults
coil. The more the conductivity of coil and fault resistance decrease, the more the electromotive flux lines pass through the assumed coil. However, the limitation of the electromagnetic flux, which entered into the linkage coil, causes more dense linkage flux in the linkage coils’ environment and symmetric distribution distortion of the transformer magnetic flux, so that search coils’ induced voltage varies in faulty state.

In the following sections, fault detection methods based on the leakage flux are classified into SBM and VBM.

### 3.1 Vibration-based method

Short-circuit current and leakage flux density bring about the increment of the electromagnetic force on transformer windings. Magnetic flux density and the electromagnetic force are decomposed into their radial and axial components as Equation (3).

\[
F = I\left(-\vec{B}_r + \vec{B}_a\right) = iF_x + jF_y
\]

where \(I\), \(F_x\), \(F_y\), \(B_r\) and \(B_a\) represent the winding section current, radial and axial components of the electromagnetic force, radial, and axial components of flux density, respectively. Equation (3) represents that radial and axial components of the electromagnetic force are directly related to the radial and axial components of the magnetic flux density [37]. The purpose of vibration analysis is to examine inter-turn faults’ impact on the transformer. Moreover, transformer vibration is a result of the electromagnetic force on the transformer winding and core. Also, Equation (3) indicates the proportional relationship between the electromagnetic forces and current. Furthermore, the current is almost sinusoidal (50 Hz), which means that the main harmonic of winding force is 100 Hz. The core vibration is a result of the magnetostriiction and magnetic forces. Figure 5 indicates the dynamic model of axial vibration according to the mass motion equation element, which is written as Equation (4).

\[
\begin{align*}
\frac{d^2z_1}{dt^2} + c_1 \frac{dz_1}{dt} + k_1z_1 + k_{11}(z_1 - z_2) &= F_1 + m_1g \\
\frac{d^2z_2}{dt^2} + c_2 \frac{dz_2}{dt} + k_1(z_1 - z_2) + k_2(z_2 - z_3) &= F_2 + m_2g \\
\frac{d^2z_n}{dt^2} + c_n \frac{dz_n}{dt} + k_{n-1}(z_{n-1} - z_n) + k_n(z_n - z_{n+1}) &= F_n + m_ng \\
\frac{d^2z_N}{dt^2} + c_N \frac{dz_N}{dt} + k_{N-1}(z_{N-1} - z_N) + k_Hz_N &= F_N + m_ng
\end{align*}
\]

(4)

To measure the vibration in the transformer, the ADXL330 sensor, a small, thin, low power, complete three-axis accelerometer with signal conditioned voltage outputs that are combined on a single monolithic IC, is used. The product measures acceleration with a minimum full-scale range of \(\pm 3g\). It can measure the static acceleration of gravity in tilt-sensing applications and dynamic acceleration resulting from motion, shock, or vibration. The sensor output is an analogue voltage proportional to axis vibration.

### 3.2 Search coil-based method

To analyse flux variations in the transformer under inter-turn winding faults, four search coils are used, which are imple-
The search coils could be installed vertically or horizontally. If the search coils are installed horizontally, all leakage fluxes are not cut off by the coils; therefore, the search coils are vertically installed, and the alignment of the search coils has been shown in Figure 6(a). The alignment of search coils on the real transformer is also shown in Figure 6(b). Besides, the numbers and locations of the installed search coils are given in Table 3.

The induced voltage in search coils is given by Equation (7). As all the parameters except $B_{\text{max}}$ are constant, the induced voltage is proportional to the flux density.

$$E_{\text{rms}} = 2\pi fNA_cB_{\text{max}}$$  \(7\)

where $B_{\text{max}}$, $A_c$, $N$, and $f$ are the maximum magnetic field amplitude, core cross-section, number of winding turns, and the frequency, respectively.

### 4 | SIMULATION AND EXPERIMENTAL RESULT

To perform experimental tests, transformer components are taken apart, and further winding is carried out. The block diagram of the laboratory setup is shown in Figure 7(a), which shows a data logging method through an experimental survey. Fault resistance in the laboratory is made by a nickel-chrome alloy that has high current crossing endurance, and its resistance is not much influenced by the environment temperature. Figure 7(c) shows the transformer, ADXL data recorders, and the sensor mounted on HV winding in phase A.

In the first scenario, the simulations are carried out for the healthy state of the transformer, and loads are at a nominal rate. Obviously, in start-up time, intrush current is created due to the core's non-linearity on the primary side, as shown in Figure 8. LV phase voltages in the steady-state are shown in Figure 9. The LV current of a transformer in the steady-state is shown in Figure 10. The induced voltage in search coils of the transformer for a healthy state is shown in Figure 11. The amplitude of induced voltages in four search coils are equal; however, the voltage angle difference between up and down search coils of each phase is $180^\circ$. To confirm the results of the simulations, the experimental tests are performed under the same conditions, and the results are shown in Figures 9–11. It is clear that the results of the laboratory tests and simulations are well analogous to each other.

In the second scenario, $3\%$ fault with $5$ mΩ fault resistance in the first layer of LV winding is created at $t = 0.8$ s. Figures 12 and 13 show the currents of the HV winding and the circulating current crossing the shortened coils. The amplitude of the circulating current in shortened coils is determined by fault intensity (the amount of insulator break down); besides, circulating current purely exists in the shortened coils, and the current of other parts remains constant and only depend on input load and voltage. The induced voltage in the search coils is shown in Figure 14.

The comparison between the faulty state and the healthy state illuminates that the induced voltage in the upper search coil of phase A, in which fault has occurred, has increased remarkably. On the other hand, the voltage of the lower coil of phase A has slightly decreased; in other experiment tests, the voltage of the coils has not changed.

#### 4.1 | Transformer leakage flux investigation in various conditions

In the following sections, the influence of different parameters on the leakage flux is investigated.
4.1.1 Studying the effect of fault location, intensity, and percent on leakage flux

To investigate the effect of fault location on leakage flux, an LV and turn-to-turn fault for three different locations of winding (up, down, and the middle of winding) are applied. According to Figure 15, when a fault occurs above the winding, the induced voltage of the upper search coil has increased whereas for the fault occurrence below the winding, the induced voltage of the underneath search coil has increased. When the fault occurs in the middle of the winding, the induced voltage in search coils has slightly changed because a little amount of leakage flux crosses the coils. Thus, fault occurrence in any part of winding impacts on the amount of leakage flux (as explained in this section) in that part and induced voltage in the nearest search coil to fault location undergoes the most change.

Surveying the effect of fault severity on flux variations is carried out by changing turns to turn fault resistance on the LV
The experiments are carried out for three different fault resistance values with constant shortened turns (1% fault above phase A). Figure 16 indicates that the more the fault severity increases, the larger the amount of flux leakage and induced voltage in the search coil becomes above phase A, where the fault occurs and increases. On the other hand, when the fault current and the leakage flux change, the faulty part is largely increased, the leakage flux of other components is decreased consequently.

In this section, the effect of the percentage of faulty windings is investigated. The percentages of the simulated faults are 3%, 7%, and 10%, respectively, and are located at the top of the winding A. The fault resistance is constant for all states, which is equal to 5 mΩ. The induced voltage on the search coils is given in Figure 17. As the fault percentage increases, the leakage flux increases; consequently, the amount of voltage induced on the search coil increases. Circulating current in short-circuited windings is shown in Figure 18. With the increasing percentage of short-circuited windings, the amount of induced voltage on the faulty windings and circulating current increases.

To examine the distribution pattern of the leakage flux on search coils, a line is placed vertically on the transformer’s core at the faulty phase side, in the middle of the search coils. This line is shown in Figure 19 on the left side. Figure 19 shows the variation of flux density on this line in different conditions. Fault severity is considered changeless for LV faults. By changing the fault’s location, flux density on the vertical line...
increases. Moreover, the amount of flux density has direct relevance to the fault severity.

4.1.2 | The effect of transformer loading rate

Due to various loading rates operation at different hours in a day, different loading rates of the transformer are applied. Figure 20 shows that induced voltage in other search coils has remarkably decreased, when the current crossing the winding decreases; however, in the winding's faulty zone, in which the circulating current is constant, leakage flux slightly changes. Accordingly, the induced voltage in search coil SCa1 has not remarkably changed.

Due to the fact that most of the transformers supply inductive loads, it is crucial to analyse the effect of power factor on the transformer's behaviour. Simulations are carried out for three types of loads: resistive load, inductive load with power factor equal to 0.9, and capacitive load with power factor equal to 0.9. For these three conditions, the fault occurs above phase A. Figure 21 depicts that the amplitude of the induced voltage in search coils has not remarkably changed; however, it has a small phase shift in comparison to a resistive load.

4.1.3 | Flux variation for fault in phase B

Due to symmetrical windings and transformer's core structure, unlike phase B, the occurred faults in phase C are similar to that of phase A. To survey leakage flux variations for faults that occurred in phase B, 3% and 8% fault above phase B are simulated. The initial current of phase B increases proportionally to the fault severity. Figure 22 shows induced voltage in search coils. The induced voltage in each four search coils has increased proportionally to the numbers of shortened turns.
4.1.4 Fault on the HV side

In this section, the fault is modelled on HV winding. Fault percentage and resistance are 0.25% and 0%, respectively. For faults on the HV side of the transformer, secondary terminal quantities will remain unchanged due to a constant leakage flux, which passes the windings before and after the fault occurrence, resulting in a constant voltage supply on the transformer windings. The induced voltage on the search coils is shown in Figure 23. According to search coils voltage waveform, where the highest voltage change has occurred in the lower search coil of phase A around the fault point, it is evident that this change has appeared as an increase in voltage. As mentioned, faults on the HV winding do not increase the current in LV winding, but change the induced voltage on the search coils.

5 PROPOSED FAULT DETECTION METHODS

In this section, two new fault detection methods are proposed.

5.1 Fault detection based on the search coil method

Here, the summation voltage of the search coils has been used to detect faults. To be more precise, the voltage of search coils SCA1 and SCA2 (VSCA1 and VSCA2) have been summed up continuously and compared with the threshold voltage. The total value of the search coils' voltage VSCA1 and VSCA2 is defined as ΔVSCA. Moreover, the total value of the search coils voltage VSCc1 and VSCc2 is defined as ΔVSCc. If the ΔVSCA or ΔVSCc becomes bigger than the threshold voltage, the fault can be detected. The flowchart of the proposed fault detection method is indicated in Figure 24. When the transformer works under a nominal load condition, the rms voltage value of ΔVSCA equals to 0.1. Moreover, the rms value of ΔVSCc equal to 0.11. To prevent misdiagnosis, the threshold voltage (VTHsc) amplitude is considered 20% higher than ΔVSCa and ΔVSCc; consequently, the threshold voltage is selected equal to 0.132. When the fault is detected, depending on the induced voltage on each search coil, the fault location is detected. Since the windings have to be entirely repaired after a fault detection, there is no need to detect the fault's exact location.

To confirm the effectiveness of the proposed method, various faults have been imposed on the transformer winding. Different fault scenarios have been simulated on the LV and HV winding side that is shown in Figure 25. The faults’ resistance and severity have been presented in Table 4. The search coils voltage variation (ΔVSCA and ΔVSCc) are demonstrated in Figure 26. It is clear that depending on the fault severity and fault location, the search coils' summation voltage has changed. As a result, as observed in Table 4, the fault detection process has been executed accurately for faults in the upper and lower part of the winding, but the fault detection in the middle of the winding has not been performed correctly. This is because the leakage flux does not pass through the middle of the winding when faults occur. To compensate this deficiency, it is recommended that another search coil is mounted in the middle of the transformer winding.

5.2 Fault detection based on vibration analysis

If an inter-turn fault occurs in the transformer winding, the current, leakage flux and the electromagnetic force increase.
When electromagnetic forces increase in axial and radial directions, the vibration of the windings also increases. If fault severity increases, the vibration amount increases too. If the fault occurs near the vibration sensor’s location, vibration will be larger than the case in which fault is far from the sensor. However, various tests show that for different fault location, the vibration signal increases in each phase that is, because the HV and LV windings are closely connected and wrapped with the insulation’s ribbons around the LV and HV windings that anchor the winding tightly. Therefore, to detect the transformer fault in each phase by this method, one sensor for each phase must be utilized. Different parameters impact the transformer vibration; for instance, the environment noise and transformer’s load are two significant parameters for vibration. Because internal faults cause the frequency of 100 Hz, to detect faults based on vibration, in different amounts of loading, the amount of vibration in the frequency range of 100 Hz has been recorded. To identify the fault, the loading value is first measured online, and using a lookup table, the amount of vibration is obtained in the normal operating mode of the transformer. Then, the vibration is measured online, and the 100-Hz frequencies related to X-axis and Y-axis are extracted using the FFT. After that, the amount of vibration measured online is compared with the vibration of the lookup table, and ΔFFT(X) and ΔFFT(Y) is obtained. If the obtained value is higher than the vibration threshold (VTHV), the transformer has a fault. The online process of detecting fault has been proposed in Figure 27. Various tests have been performed on the transformer to determine the value of the vibration threshold. Since the vibration increases with increasing the load of the transformer, the value of the vibration threshold is considered in the unloaded state. In the unloaded state, various tests have been performed. For large fault resistors (low fault current), the amount of vibration changes was small, and VBM cannot detect the fault. Various tests showed that the fault could be detected from about 3% for the LV winding and 0.025% for the HV winding. So that, the threshold value regarding changes in the amount of vibration at a frequency of 100 Hz is considered equal to 0.01.

To verify this claim, four case studies are discussed, as shown in Table 5. Y-axis frequency analysis for these cases is shown in Figure 28, and it can be perceived that the DC amount of vibration is increased in a fault condition, and in the fourth case, the vibration is more severe in comparison to the second case with the same fault severity because the sensor is mounted close to the top of the winding. In the second case, the fault is in the middle of the winding, and the DC amount is larger than the healthy state. Figure 28 shows that at a frequency of 100 Hz with increasing fault severity, the winding vibration increases based on Equation (3).

Figure 29 shows the vibration frequency spectrum along the X-axis. These results express that the vibration frequency analysis can be used as an effective method for inter-turn fault detection. The fault detection results for the VBM are presented in Table 5. As the results show, the fault detection is carried out correctly. Various fault types, severity, and location made changes on vibration’s frequency spectrum, which can be used to detect inter-turn fault’s location and severity by artificial intelligence methods.

6 | DISCUSSION

In this section, a brief comparison between VBM and SCBM is carried out. The flux amount of the two methods have been compared to validate and evaluate each method’s sensitivity. To investigate the flux changes in the two proposed methods, the flux difference between the healthy and faulty conditions has been used that can be shown as: Δφ = φF − φH, where Δφ is the flux variation, φH and φF are flux variations in the healthy and faulty conditions, respectively.
In the vibration-based method, the sensor measures the amount of vibration. First, the amount of electromagnetic force is obtained using Equation (5); afterwards, the flux density amount will be obtained using Equation (3). In this case, the differences between the vibration of the healthy state and the faulty state are used to calculate the leakage flux. Additionally, leakage flux values are calculated for all cases at the same time. The $\Delta \varphi$ value for the two methods related to 3% and 5% faults in LV winding is presented in Table 6. According to the obtained results, it is obvious that the flux quantity in the two methods confirms each other. The flux-based method experienced 46% changes, and the vibration-based method held 38% changes. The flux sensitivity regarding the fault severity variation in the leakage SCBM is higher than that of the VBM.

**TABLE 4** Test Properties for search coil method analysis

| Case # | Fault severity | Fault resistance | $\Delta$SCa (rms) | $\Delta$SCc (rms) | Detection result |
|--------|----------------|------------------|-------------------|-------------------|------------------|
| Case 1 | 5%             | 10 mΩ            | 1.08              | 0.119             | Detected         |
| Case 2 | 5%             | 10 mΩ            | 0.6               | 0.09              | Not detected     |
| Case 3 | 5%             | 10 mΩ            | 0.07              | 0.095             | Not detected     |
| Case 4 | 5%             | 10 mΩ            | 0.52              | 0.122             | Detected         |
| Case 5 | 5%             | 20 mΩ            | 1.09              | 0.129             | Detected         |
| Case 6 | 5%             | 20 mΩ            | 0.04              | 0.0918            | Detected         |
| Case 7 | 5%             | 10 mΩ            | 1.08              | 0.167             | Detected         |
| Case 8 | 1%             | 5 mΩ             | 0.14              | 0.29              | Detected         |
| Case 9 | 3%             | 5 mΩ             | 0.46              | 0.38              | Detected         |
| Case 10| 0.25%          | 0 mΩ             | 0.141             | 0.0986            | Detected         |
| Case 11| 0.25%          | 0 mΩ             | 4.1               | 0.35              | Detected         |
| Case 12| 0.25%          | 0 mΩ             | 4.04              | 0.31              | Detected         |

**FIGURE 26** Supplementation of search coil voltage for various faults: (a) cases 1–8 and (b) cases 9–12

**FIGURE 27** Proposed fault detection method based on VBM. VBM, vibration-based method
TABLE 5 Test properties for vibration method analysis

| Cases | Fault severity | Fault location | Phase   | Detection result |
|-------|----------------|----------------|---------|------------------|
| Case 1 | Healthy        | –              | –       | Detected         |
| Case 2 | 5% LV winding  | Mid of winding | A phase | Detected         |
| Case 3 | 3% LV winding  | Down of winding| A phase | Detected         |
| Case 4 | 5% LV winding  | Top of winding | A phase | Detected         |

Abbreviation: LV, low voltage.

FIGURE 28 FFT analysis of the Y-axis vibration. FFT, fast Fourier transform

FIGURE 29 FFT analysis of the X-axis vibration. FFT, fast Fourier transform

Since in the SCBM method, the transformer's structure needs to be taken apart, this method costs more in comparison with the VBM method. Besides, isolation limitation might lead to additional costs in the SCBM method. Although both methods have appropriate online detection capability, the cost of online detection in VBM is less than that of SCBM. VBM method is incapable of fault location detection, but SCBM provides precise fault location identification; however, the VBM method may provide fault location detection with the help of neural network methods. Furthermore, SCBM operates better than VBM in fault severity detection. Both methods have identical complexity, which is required software and hardware tools for signal analysis. Besides, the VBM method's accuracy is less than that of the SCBM method because the vibration can be affected by other parameters such as the transformer's core vibration, which decreases the accuracy of the VBM. Furthermore, changes in the transformer structure in the SCBM are considerable because the transformer must be disassembled to install search coils. On the other hand, the vibration method does not require disassembling the transformer, and the installed sensor on the transformer does not cause significant changes. A comparison of different characteristics of the leakage-based methods for the understudy transformer is presented in Figure 30.

7 | CONCLUSION

Here, the effect of the inter-turn winding faults on leakage fluxes is analysed. During winding faults, the coil's voltage decreases and generates a circulating current in linkage coils, which limits the flux interring the coil. Accordingly, this causes the increment of leakage fluxes in the zone of shortened turns. The more the fault's severity, the more considerable amount of leakage fluxes pass the coils. Other parts' fluxes will not remarkably change in minor faults' condition but when there are severe faults, leakage flux of all the coils change. Here, SCBM is used as a simple and effective method to detect inter-turn winding faults since leakage flux is sensitive to the fault location and severity. Also, there is a possibility of fault location and severity detection in this method. Besides, search coils can be used for online monitoring of the transformers since the amount of induced voltage in search coils is negligible.
Simulation results demonstrate that by changing the fault severity, the transformer leakage flux changes leading to increment in the search coils’ induced voltage. Thus, it is possible to use search coils for detection of winding fault severity and location. Moreover, analysing the steady-state vibrations and investigating the results show that faulty windings can be distinguished from normal windings. The sensor used for vibration measurement is commercially suitable, so this method is cost-effective when compared with other methods.

REFERENCES

1. Luo, M., Dujic, D., Allmeling, J.: Leakage flux modelling of medium-voltage phase-shift transformers for system-level simulations. IEEE Trans. Power Electron. 34(3), 2635–2654 (2019). https://doi.org/10.1109/TPEL.2018.2837052

2. Haghihojoo, F., Mostafaei, M., Mohammadi, H.: A new leakage flux-based technique for turn-to-turn fault protection and faulty region identification in transformers. IEEE Trans. Power Deliv. 33(2), 671–679 (2018). https://doi.org/10.1109/TPWRD.2017.2688419

3. Hajiaghasi, S., et al.: Transformer leakage flux frequencies analysis under internal windings faults. In: Proceedings of the IICE 2019 – 27th Iranian conference on electrical engineering, pp. 709–713. IEEE, Yazd, Iran (2019). https://doi.org/10.1016/IranianCEE.2019.8786753

4. Esponda, H., et al.: Extended second central moment approach to detect turn-to-turn faults in power transformers. IET Electr. Power Appl. 13(6), 766–775 (2019). https://doi.org/10.1049/iet-epa.2018.5689

5. Hajiaghasi, S., Abbassadeh, K., Salemlia, A.: A new approach for transformer interturn faults detection using vibration frequency analysis. Iran. J. Electr. Electron. Eng. 15(16), 14. http://ijsee.iust.ac.ir/article-1-1228-en.html

6. Cabañas, M.F., et al.: A new online method based on leakage flux analysis for the early detection and location of insulating failures in power transformers: application to remote condition monitoring. IEEE Trans. Power Deliv. 22(3), 1591–1602 (2007). https://doi.org/10.1109/TPWRD.2006.881620

7. Paydarnia, H., Hajiaghasi, S., Abbassadeh, K.: Improved structure of PNN using PCA in transformer fault diagnostic. Arab. J. Sci. Eng. 39(6), 4845–4851 (2014). https://doi.org/10.1007/s13369-014-1004-z

8. Asadi, N., Kelk, H.M.: Modelling, analysis, and detection of internal winding faults in power transformers. IEEE Trans. Power Deliv. 30(6), 2419–2426 (2015). https://doi.org/10.1109/TPWRD.2015.2431972

9. Haghihojoo, F., Mostafaei, M., Mohammadi, H.: A new leakage flux based technique for turn to turn fault protection and faulty region identification in transformers, IEEE Trans. Power Deliv. 33(2), 671–679 (2017). https://doi.org/10.1109/TPWRD.2017.2688419

10. Haghihojoo, F., Mostafaei, M.: Flux-based turn-to-turn fault protection for power transformers. IET Gener. Transm. Distrib. 10(5), 1154–1165 (2016). https://doi.org/10.1049/iet-gtd.2015.0738

11. Behjat, V., et al.: Diagnosing shorted turns on the windings of power transformers based upon online FRA using capacitive and inductive couplings. IEEE Trans. Power Deliv. 26(4), 2123–2133 (2011). https://doi.org/10.1109/TPWRD.2011.2151285

12. Abu-Siada, A., Hmood, S.: A new fuzzy logic approach to identify power transformer criticality using dissolved gas-in-oil analysis. Int. J. Electr. Power Energy Syst. 67, 401–408 (2015). https://doi.org/10.1016/j.ijepes.2014.12.017

13. Ghoneim, S.S.M., Taha, I.B.M.: A new approach of DGA interpretation technique for transformer fault diagnosis. Int. J. Electr. Power Energy Syst. 81, 265–274 (2016). https://doi.org/10.1016/j.ijepes.2016.02.018

14. De Faria, H. Jr., Costa, J.G.R.: A review of monitoring methods for predictive maintenance of electric power transformers based on dissolved gas analysis. Renew. Sustain. Energy Rev. 46, 201–209 (2015)

15. Behjat, V., Mahvi, M.: Localising low-level short-circuit faults on the windings of power transformers based on low-frequency response measurement of the transformer windings, IET Electr. Power Appl. 9(8), 533–539 (2015). https://doi.org/10.1049/iet-epa.2014.0182

16. Behjat, V., et al.: Sweep frequency response analysis for diagnosis of low level short circuit faults on the windings of power transformers: an experimental study. Int. J. Electr. Power Energy Syst. 42(1), 78–90 (2012). https://doi.org/10.1016/j.ijepes.2012.03.004

17. Khanali, M., et al.: Study on locating transformer internal faults using sweep frequency response analysis. Electr. Power Syst. Res. 145, 55–62 (2017). https://doi.org/10.1016/j.epsr.2016.11.016

18. Oliveira, L.M.R., Cardoso, A.J.M.: Comparing power transformer turn-to-turn faults protection methods: negative sequence component versus space-vector algorithms. IEEE Trans. Ind. Appl. 53(3), 2017–2025 (2017). https://doi.org/10.1109/TIA.2016.2613506

19. Zacharias, D., Gokaraju, R.: Prototype of a negative-sequence turn-to-turn fault detection scheme for transformers. IEEE Trans. Power Deliv. 31(1), 122–129 (2016). https://doi.org/10.1109/TPWRD.2015.2483524

20. Mirzaei, H.R., et al.: A novel method for ultra-high-frequency partial discharge localization in power transformers using the particle swarm optimization algorithm. IEEE Electr. Insul. Mag. 29(2), 26–39 (2013). https://doi.org/10.10109/MEI2013.6457597

21. Mirzaei, H., et al.: Advancing new techniques for UHF PD detection and localization in the power transformers in the factory tests. IEEE Trans. Dielectr. Electr. Insul. 22(1), 448–455 (2015). https://doi.org/10.1109/TDEIE.2014.004249

22. Karam, H., et al.: Simultaneous radial deformation and partial discharge detection of high-voltage winding of power transformer. IET Electr. Power Appl. 14(3), 383–390 (2020). https://doi.org/10.1049/iet-epa.2019.0528

23. Venikar, P.A., et al.: Search coil based online diagnostics of transformer internal faults. IEEE Trans. Power Deliv. 32(6), 2520–2529 (2017). https://doi.org/10.1109/TPWRD.2017.2682083

24. Wiszniewski, A., Rebizant, W., Schiel, L.: New algorithms for power transformer inter-turn fault protection. Electr. Power Syst. Res. 79(10), 1454–1461 (2009). https://doi.org/10.1016/j.epsr.2009.04.021

25. Masoum, A.S., et al.: Online transformer internal fault detection based on instantaneous voltage and current measurements considering impact of harmonics. IEEE Trans. Power Deliv. 32(2), 587–598 (2017). https://doi.org/10.1109/TPWRD.2014.2358072

26. Balaga, H., Gupta, N., Vishwakarma, D.N.: GA trained parallel hidden layered ANN based differential protection of three phase power transformer. Int. J. Electr. Power Energy Syst. 67, 286–297 (2015). https://doi.org/10.10109/ijepes.2014.11.028

27. Dashti, H., Sanaye-Pasand, M.: Power transformer protection using a multiregion adaptive differential relay. IEEE Trans. Power Deliv. 29(2), 777–785 (2014). https://doi.org/10.1109/TPWRD.2013.2280023

28. Sevov, L., Khan, U., Zhang, Z.: Enhancing power transformer differential protection to improve security and dependability. IEEE Trans. Ind. Appl. 53(3), 2642–2649 (2017). https://doi.org/10.1109/TIA.2017.2670525

29. Wang, M.-H.: Extension neural network for power transformer incipient fault diagnosis. IEEE Proc. Gener. Transm. Distrib. 150(6), 679 (2003). https://doi.org/10.1049/ip-gtd:20030901

30. Bagheri, S., Moravej, Z.: Classification and discrimination among winding mechanical defects, internal and external electrical faults and inrush current of transformer, IEEE Trans. Ind. Inform. 14(2), pp. 483–493, (2017). https://doi.org/10.1109/TII.2017.2720691

31. Rahmatian, M., et al.: Insulation failure detection in transformer winding using cross-correlation technique with ANN and k-NN regression method during impulse test. Int. J. Electr. Power Energy Syst. 53(1), 209–218 (2013). https://doi.org/10.1016/j.ijepes.2013.04.020

32. Malik, H., et al.: Application of neuro-fuzzy scheme to investigate the winding insulation paper deterioration in oil-immersed power transformers.
33. Zhou, H., et al.: Transformer winding fault detection by vibration analysis methods. Appl. Acoust. 114, 136–146 (2016). https://doi.org/10.1016/j.apacoust.2016.07.024

34. Bagheri, M., Phung, B.T.: Frequency response and vibration analysis in transformer winding turn-to-turn fault recognition. In: Proceedings of the 2016 international conference on smart green technology in electrical and information systems (ICSGTEIS), pp. 10–15 (2016). https://doi.org/10.1109/ICSGTEIS.2016.7885758

35. Yang, Y., et al.: Electromagnetic vibration noise analysis of transformer windings and core. IET Electr. Power Appl. 10(4), 251–257 (2016). https://doi.org/10.1049/iet-epa.2015.0309

36. Ahn, H.M., et al.: Finite-element analysis of short-circuit electromagnetic force in power transformer. IEEE Trans. Ind. Appl. 47(3), 1267–1272 (2011). https://doi.org/10.1109/TIA.2011.2126031

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