Converter Transformer Winding Mechanical Condition Detection Using Online Vibration Frequency Response Analysis Method

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The harmonic current and vibration of the converter transformer are effective information for detecting winding mechanical faults. This paper proposes an online vibration frequency response analysis (VFRA) method and constructs a novel vibration frequency response function (VFRF), where the VFRF is defined as the ratio of vibration acceleration to current squared. A harmonic loading system simulating the actual operating situation of the converter transformer is established, and it is verified by numerical analysis and experimental methods that online VFRA is a simpler and more convenient method for winding mechanical condition detection than offline VFRA. The effects of different factors such as current magnitude and harmonic content on the online VFRA are investigated, and the converter transformer winding mechanical condition is detected by combining the VFRF trace with two numerical indices of relative factor and improved expectation. Laboratory experiments demonstrate that the online VFRA has high stability and successfully identify winding looseness faults of different degrees. Compared with the traditional frequency response analysis (FRA) and short-circuit impedance (SCI) methods, the online VFRA has higher sensitivity and detection capability for winding mechanical faults, and is a better method for online monitoring of winding mechanical condition.

1 INTRODUCTION

The converter transformer is one of the most crucial apparatuses in the HVDC transmission project. It plays a role in connection and coordination between the AC power grid and the DC line [1-3]. Due to the particularity of its location, the converter transformer bears a large amount of harmonic currents in addition to the power frequency current [4]. The harmonic currents have a considerable impact on the winding vibration, which increases the vibration amplitude, and makes the winding clamping pressure drop and winding looseness fault occur [5]. If the converter transformer suffers from an external short-circuit shock, the winding mechanical structure is easily destroyed, which in turn causes more serious deformation fault [6]. According to relevant surveys and statistics [7, 8], winding mechanical failure has developed into a major fault in converter transformer. Therefore, early detection of winding mechanical fault is crucial.

Many methods have been proposed to detect winding mechanical faults, for example, short-circuit impedance method (SCI) [9], sweep frequency impedance method (SFI) [10] and frequency response analysis method (FRA) [11, 12]. Although these methods can detect serious faults such as winding deformation, they can hardly reflect minor mechanical faults such as winding looseness. Vibration-based measurement method has become the main means of monitoring the winding mechanical condition by virtue of its high sensitivity to winding mechanical faults [13, 14]. In particular, the vibration frequency response analysis (VFRA) [15, 16] is an effective method to detect winding looseness fault. The SCI, SFI, FRA methods treat the winding as a circuit model consisting of resistance, inductance and capacitance [9-12], [17], so it is difficult to detect minor faults such as winding looseness (almost no change in circuit parameters). The VFRA equates the winding as a mechanical model composed of mass, spring and damping, which reflects the essential structural features of the windings [18]. Thus, VFRA can more easily detect different types and degrees of winding mechanical faults.

The existing VFRA is mainly proposed according to the features of ordinary power transformers. Because the winding of ordinary power transformer flows through the power frequency current, like the conventional FRA, VFRA also requires the external input from sweep power supply [19], [20]. The basic operation [21]: one side of the winding is short-circuited and sinusoidal currents with constant amplitude and different frequencies are injected into the other side of the winding, and then the winding vibration signals are collected. In [22], two methods, VFRA and conventional FRA, were used to detect winding mechanical faults, and the tests showed that VFRA has higher detection sensitivity for
different mechanical faults compared to the conventional FRA. The different quantitative indicators in [23] were combined to identify winding looseness and deformation faults based on the verification that VFRA is reproducible, while pointed out the problem that conventional FRA cannot detect winding looseness fault. In [24], the VFRF from which the modal characteristics of transformer windings were extracted for diagnosing transformer mechanical faults, was measured and analyzed, demonstrating that VFRA can be applied to all types of transformers. The relationship between VFRF and short-circuit shock in a 220 kV transformer was studied in [25]. The results showed that VFRA is easier to identify winding mechanical faults than the SCI method.

The above research results show that VFRA has high sensitivity and identification accuracy for transformer winding mechanical fault and is of great significance for diagnosing winding mechanical fault. However, the existing VFRA is still an offline detection method (denoted as offline VFRA in this paper), which requires transformer shutdown and is extremely inconvenient. Meanwhile, there are numerous problems. For one thing, transformers are generally large structural equipment, the small current output from the sweep power supply is difficult to generate winding vibration. For another thing, offline VFRA directly takes the collected acceleration as the VFRF, and the stability of the sweep power supply output affects the accuracy of the test result. Many of the above factors limit the field application of offline VFRA to a certain extent. Different from ordinary power transformer, the converter transformer winding flow a large amount of harmonic currents, generating high amplitude and multi-frequency electromagnetic forces, which are equivalent to the external input of the sweep power supply. Therefore, it enables the online application of VFRA.

In this paper, a novel online VFRA method for detecting the winding mechanical condition is proposed using the unique harmonic currents of the converter transformer. The expression form of online VFRF is derived from the established winding vibration model. The numerical analysis and experimental methods verify the consistency between the online VFRA and the offline VFRA. The actual harmonic current loading platform of the converter transformer is built, and it is found that the influence of different factors on the online VFRA is negligible. The online VFRA is applied to a scaled-down test converter transformer, and different winding looseness levels are successfully identified according to the variation patterns of the VFRF trace and numerical indices. The main contributions of this paper are summarized as follows.

1. A novel VFRA is proposed using the unique harmonic currents of the converter transformer. The method develops VFRA from an offline detection means to an online monitoring method, which greatly simplifies the measurement process, saves measurement time and improves the efficiency of winding mechanical fault identification.

2. A numerical analysis method of vibration response different from finite element method is proposed. The method can be used to analyze winding vibration characteristics and predict winding mechanical faults.

(3) Based on online VFRA, the trace development of VFRF and the variation pattern of numerical indices after the converter transformer winding looseness are quantitatively analyzed. The mechanical condition detection method can identify winding looseness faults of different degrees and can be implemented to online monitor the winding mechanical condition.

2 | ONLINE VFRA METHODOLOGY

2.1 | Establishment of Winding Vibration Model

2.1.1 | Vibration modal

The winding structure of the converter transformer is the same as that of the ordinary power transformer. The axial vibration of the disk type winding can be equivalent to a multi-degree-of-freedom mass-spring-damping model [26]. The winding axial vibration model is shown in Fig. 1. In the model, \( m \) is the mass of winding disk, \( c \) is the equivalent damping, \( k \) is the equivalent stiffness of the spacer. \( F \) is the electromagnetic force (EMF). The dynamics equation is

\[
\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}
\]

where \( \mathbf{M} \) is the mass matrix, \( \mathbf{C} \) is the damping coefficient matrix, and \( \mathbf{K} \) is the stiffness coefficient matrix. \( \mathbf{F} \) is the EMF matrix. \( \mathbf{x}, \dot{\mathbf{x}} \) and \( \ddot{\mathbf{x}} \) are the displacement, velocity, and acceleration matrix, respectively.

Equation (1) reflects the vibration characteristics and mechanical condition of the converter transformer winding. The parameters involved are mainly the magnetic field and EMF.

\[
\begin{align*}
\begin{array}{c}
\mathbf{x}_1 \\
\mathbf{x}_2 \\
\mathbf{x}_3 \\
\vdots
\end{array}
\end{align*}
\]

\[
\begin{align*}
\begin{array}{c}
\mathbf{c}_1 \\
\mathbf{c}_2 \\
\mathbf{c}_3 \\
\vdots
\end{array}
\end{align*}
\]

\[
\begin{align*}
\begin{array}{c}
k_1 \\
k_2 \\
k_3 \\
\vdots
\end{array}
\end{align*}
\]

\[
\begin{align*}
\begin{array}{c}
\mathbf{F}_1 \\
\mathbf{F}_2 \\
\mathbf{F}_3 \\
\vdots
\end{array}
\end{align*}
\]

Fig. 1. Winding axial vibration model.

2.1.2 | Magnetic field

Different from the power frequency current flowing through ordinary power transformer, the currents of converter transformer winding are harmonic currents with distinct \( 6k \pm 1 \) \((k = 1, 2, 3, \ldots) \) [27]. Consequently, the load currents of the converter transformer can be expressed as

\[
i = \sum I_i \cos(\lambda \cdot 2\pi t + \phi_i)
\]

where \( \sum I_i \) \((i = 1, 5, 7, 9, 11, \ldots) \) is the summation of different frequency currents. \( \lambda = 6k \pm 1 \), \( \lambda = 1, 5, 7, 9, 11, \ldots \) \( t \) is the amplitude of the current. \( \omega_n = 2\pi f_n \) \((f_n = 50 \text{ Hz}) \) is the angle frequency, \( \phi \) is the phase angle of the current.
The magnetic field of the converter transformer winding is generated by the load currents of different frequencies. The superimposed magnetic fields generated by the coils are equivalent to the magnetic field of the winding. Fig. 2 shows the equivalent calculation model of the converter transformer winding magnetic field. In the figure, \( r_1 \ldots r_m \) refer to the coil radius, \( h_1 \ldots h_n \) to the coil height.

According to the Biot-Savart law, the radial magnetic field of the winding is

\[
B = \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{\mu_0 h_i}{2 \pi r_i \sqrt{r_i^2 + x^2 + h_i^2 + 2r_i x}} \left( E - K \right) = k_s (3)
\]

where \( \mu_0 \) is the permeability, \( n \) is the number of winding turns, and \( m \) is the number of coils in parallel.

![Fig.2. Equivalent calculation model of winding magnetic field.](Image)

### 2.1.3 EMF

The winding EMF is produced under the combined action of the current and the magnetic field. For an ordinary power transformer, the EMF generated at the power frequency current is

\[
F = B i l = k_s I_{lm}^2 \left( \frac{1}{2} + \frac{1}{2} \cos(2\omega t + 2\phi) \right) (4)
\]

where \( l \) is the coil length and \( I_{lm} \) is the magnitude of the power frequency current.

Clearly, the VFRA of the ordinary power transformer requires an external input from the sweep power supply due to the low harmonic content of the winding EMFs. In contrast, there are \( k \times 100 \) Hz EMFs in the converter transformer winding, distributed over the entire frequency band. The EMFs generated at the harmonic currents are

\[
F = B i l = k_s I_{lm}^2 \left( \frac{1}{2} + \frac{1}{2} \cos(2\omega t + 2\phi) \right) \left( \sum_{j=1}^{l} I_{j}^2 + \frac{1}{2} \sum_{j=1}^{l} \sum_{k=1}^{j-1} \cos(\lambda_j - \lambda_k) \left( \phi_j + \phi_k \right) + \frac{1}{2} \sum_{j=1}^{l} I_{j}^2 \sum_{k=1}^{j-1} \sum_{l=1}^{j} \cos(\lambda_j - \lambda_k) \left( \phi_j + \phi_k \right) \right) \left( 5 \right)
\]

where \( \sum_2^* \) is the multiplication of different frequency currents, and then summed, \( \lambda_1 = \omega t + 1, \lambda_2 = 6k_2 + 1, \lambda_1 = 5, 7, 9, 11, \ldots, \lambda_2 = 1, 5, 7, 9, 11, \ldots \), and \( \lambda_1 \neq \lambda_2 \).

Fig. 3 shows the EMFs spectrum of ordinary power transformer and converter transformer in operation. The y-axis is the harmonic ratio for EMFs, expressed as

\[
HRF = \frac{F_k}{F_1} \times 100\% (6)
\]

where \( F_1 \) is the fundamental frequency EMF and \( F_k \) is the harmonic EMF. \( F \times \omega \) is obtained by the current squared.

As shown in Fig. 3, the converter transformer is subjected to massive EMF harmonics compared to the ordinary transformer. The maximum EMF harmonic ratio of ordinary transformer is 2.25% of 200Hz, while the maximum EMF harmonic ratio of converter transformer is 36.84% of 200Hz, which is 16.37 times of ordinary transformer. The EMF harmonic ratios within 800Hz are distributed between 15% and 20%, and the other frequency points also basically reach more than 5%. Further calculation, the total harmonic distortion for EMFs of ordinary transformer is only 3.78%, and the total harmonic distortion for EMFs of converter transformer is 57.12%, which means that the EMFs with larger amplitude are distributed at \( k \times 100 \) Hz and can excite the greater winding vibrations. Therefore, the high amplitude and multi-frequency EMFs are analogous to the external input of sweep power supply, enabling the online application of VFRA.

### 2.2 Online VFRA

The VFRF reflects the relationship between the response (acceleration) and the excitation (EMF), and describes the essential features for the internal structure of the dynamical system. The winding VFRF is not influenced by external excitation but is only related to the mechanical structure of the winding itself which is composed of mass, damping and stiffness together. Hence, VFRA is an effective method to detect the winding mechanical condition.

The winding vibration model of the converter transformer is a single-input, multiple-output mechanical system, i.e., the load current (or EMF) is a single-input excitation, and the different winding disk vibrations are multiple-output responses. Converting equation \( 1 \) to frequency domain by Fourier transform [19].

\[
(-\omega^2 M + j\omega C + K)x(j \omega) = k_s l^2 (j \omega) (7)
\]

The VFRF of the winding displacement is

\[
H_x(j \omega) = \frac{x(j \omega)}{k_s l^2 (j \omega)} = (-\omega^2 M + j\omega C + K)^{-1} (8)
\]

Similarly, the VFRF of the winding acceleration is
\[ H_{x}(j\omega) = \frac{\hat{x}(j\omega)}{k_{g}l^{2}(j\omega)} = (M - j\frac{1}{\omega}C - \frac{1}{\omega^{2}}K)^{-1} \] (9)

From equation (9), the VFRF of the winding acceleration is the ratio of acceleration to EMF in the frequency domain. However, the winding EMF is difficult to obtain in practice, and equation (9) can be further turned into a calculable form.

\[ \overline{H}_{x}(j\omega) = \frac{\hat{x}(j\omega)}{\hat{i}(j\omega)} = \frac{k_{g}/l^{2}}{(M - j\frac{1}{\omega}C - \frac{1}{\omega^{2}}K)} \] (10)

where \( \hat{x}(j\omega) \), \( \hat{i}(j\omega) \) are the Fourier transforms of the converter transformer vibration acceleration and current squared, respectively.

Ultimately, the online VFRF is defined as the ratio of the winding vibration acceleration to the current squared. Table I shows the comparison between online VFRF and offline VFRF. The differences between the two are summarized as follows.

(1) In terms of operation state, offline VFRF requires the transformer to be out of service, which is an offline detection means; while online VFRF is an online monitoring method for operating converter transformers.

(2) In terms of excitation, the offline VFRF has to be excited with the help of a constant external input from a sweep power supply, and the online VFRF is excited by its own harmonic currents.

(3) In terms of signal acquisition, offline VFRF has to continuously acquire vibration signals of different frequencies, which takes a long time; online VFRF only acquires current signal and vibration signal simultaneously, which can be done instantly.

(4) In terms of calculation, offline VFRF takes processing vibration signals of different frequencies, which is data-intensive, time-consuming and inefficient; online VFRF only follow Equation (10) to obtain VFRF at one time.

Therefore, the VFRA proposed in this paper is a fast and effective online monitoring method. Simply by collecting the winding vibration acceleration signal and current signal of the operating converter transformer, the winding VFRF and mechanical condition can be obtained.

### Table I

<table>
<thead>
<tr>
<th>Detection method</th>
<th>Offline VFRA</th>
<th>Online VFRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation state</td>
<td>Out of service</td>
<td>In operation</td>
</tr>
<tr>
<td>External device</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Test time</td>
<td>Long</td>
<td>Extremely short</td>
</tr>
<tr>
<td>Detection way</td>
<td>Offline</td>
<td>Online</td>
</tr>
</tbody>
</table>

### 3 | EQUIVALENCE VERIFICATION OF ONLINE VFRA AND OFFLINE VFRA

#### 3.1 | Numerical Equivalence Verification of Online VFRA and Offline VFRA

The vibration acceleration of offline VFRA is obtained with different frequencies of constant current, and its VFRF reflects the amplitude-frequency characteristics of acceleration (m/s²) and frequency (Hz) [19-23]. The VFRF of online VFRA represents the amplitude-frequency characteristics of [acceleration/current squared] (g/A²) and frequency (Hz). The numerical analysis method is used to verify the consistency between the two.

First, equation (1) is converted into a state equation (11) and solved numerically using the Runge-Kutta method.

\[
\begin{align*}
\dot{x}_{f}^{j} &= x_{a_{j}}^{j} \\
\dot{x}_{a_{j}}^{j} &= [B_{f}ll + c_{j}x_{a_{j-1}}^{j} - (c + c_{j})x_{a_{j}}^{j} \\
&+ c_{j}x_{a_{j-1}}^{j} + k_{j}x_{j-1}^{j} - (k + k_{j})x_{j}^{j} + k_{j}x_{j-1}^{j}] / m_{j}
\end{align*}
\] (11)

where \( x_{f}^{j}, x_{a_{j}}, x_{a_{j}}^{j} \) are the state parameters of the state equation, which can be understood as displacement \( x_{j} \), velocity \( x_{a_{j}} \), and acceleration \( x_{a_{j}}^{j} \). B, c, k, m are the magnetic field, damping coefficient, stiffness coefficient, and winding disk mass, respectively.

The measured harmonic current of the in-operation converter transformer is used as current \( i_{0} \) for the numerical analysis method and the subsequent experimental method, where 125A is the power frequency rated current and other harmonic currents are converted in equal proportion. The initial displacement and initial velocity are zero, the simulation time step is 1/10240s, and the total time is 2s.

The calculation process of the two VFRA is as follows.

**Scenario I: Offline VFRA**

Input: \( M, C, K, k_{g}, l, i \)
Output: Vibration acceleration (m/s²)
1. \( f = 1 \rightarrow 1000 \) do
2. \( i_{f} = I \cos(2\pi f \times t) \)
3. \( \dot{x}_{f_{j}} = A_{f_{j}} \cos(2\pi(2f) \times t) \) ←
\[
\begin{align*}
\dot{x}_{f}^{j} &= x_{a_{j}}^{j} \\
\dot{x}_{a_{j}}^{j} &= [B_{f}ll + c_{j}x_{a_{j-1}}^{j} - (c + c_{j})x_{a_{j}}^{j} \\
&+ c_{j}x_{a_{j-1}}^{j} + k_{j}x_{j-1}^{j} - (k + k_{j})x_{j}^{j} + k_{j}x_{j-1}^{j}] / m_{j}
\end{align*}
\]
4. end for
5. Offline VFRF = \( \dot{x}_{f_{j}}^{j}(j\omega) \)

**Scenario II: Online VFRA**

Input: \( M, C, K, k_{g}, l, i \)
Output: Vibration acceleration/current squared (g/A²)
1. \( i = \sum_{j=1}^{1000} I \cos(2\pi f \times t) \)
2. obtain vibration acceleration
\[
\ddot{x} = \sum_{j=1}^{1000} A_{f_{j}} \cos(2\pi(2f) \times t) \leftarrow
\begin{align*}
\dot{x}_{f}^{j} &= x_{a_{j}}^{j} \\
\dot{x}_{a_{j}}^{j} &= [B_{f}ll + c_{j}x_{a_{j-1}}^{j} - (c + c_{j})x_{a_{j}}^{j} \\
&+ c_{j}x_{a_{j-1}}^{j} + k_{j}x_{j-1}^{j} - (k + k_{j})x_{j}^{j} + k_{j}x_{j-1}^{j}] / m_{j}
\end{align*}
\]
4. Online VFRF = \( \ddot{x}(j\omega) / \dot{i}(j\omega) \)

Fig. 4 shows the VFRFs of the offlineVFRA and online
VFRA calculated using the numerical analysis method. Where the unit on the left side of y-axis is acceleration (m/s²), which indicates offline VFRA, and the unit on the right side of y-axis is [acceleration/current squared] (g/A²), which indicates online VFRA. Although the units and magnitudes of online VFRA and offline VFRA are different, both have identical VFRF from the curve trace and curve variation trend, which proves that they are perfectly consistent. The online VFRA contains a VFRF of $k \times 100$Hz, fully illustrating that online VFRA can reflect the internal mechanical condition of the winding.

![Graph](image)

**Fig.4. Numerical equivalence validation results for offline VFRA and online VFRA.**

### 3.2 Experimental platform construction

To simulate the actual operating situations of the converter transformer, a harmonic loading system and a vibration monitoring platform are built, as shown in Fig. 6.

![Diagram](image)

**Fig.5. Experimental platform (a) harmonic loading system (b) vibration monitoring platform.**

The harmonic loading system is mainly composed of controllable harmonic power supply, medium-frequency transformer, and test converter transformer. The controllable harmonic power supply can simultaneously generate several harmonic currents of different frequencies. The amplitude and phase of each harmonic current component are continuously adjustable. The output frequency range of the system is (0,2500] Hz, which meets the harmonic loading requirements and actual operating environments of the converter transformer. The medium-frequency transformer is a dry-type transformer, which applies the harmonic currents to the converter transformer. Based on the electrical and structural parameters of the in-service converter transformer operating at the Zhongzhou converter station of the ±800kV Haminan-Zhengzhou UHVDC Transmission Project, a scaled-down test converter transformer is customized.

Depending on the number of winding disks and the winding structure, a total of 11 accelerometers PCB352C65 are arranged on the winding. The accelerometer weighs only 2 grams, minimizing the impact of sensor weight on vibration testing. The parameters of accelerometer PCB352C65 are shown in Table II and the specific measuring point positions on the converter transformer winding are shown in Fig. 5. In addition, the system is equipped with an AC ammeter to collect the current signal synchronized with the vibration signal.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>PARAMETERS OF ACCELEROMETER PCB352C65</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>Sensitivity (mV/g)</td>
<td>100</td>
</tr>
<tr>
<td>Measuring range (g pk)</td>
<td>±50</td>
</tr>
<tr>
<td>Resolution RMS (g rms)</td>
<td>0.00016</td>
</tr>
<tr>
<td>Frequency range (Hz)</td>
<td>0.5-10000</td>
</tr>
<tr>
<td>Resonance frequency (Hz)</td>
<td>≥35000</td>
</tr>
<tr>
<td>Weight (grams)</td>
<td>2</td>
</tr>
</tbody>
</table>

### 3.3 Experimental Equivalence Verification of Online VFRA and Offline VFRA

The equivalence of online VFRA and offline VFRA is verified from both theoretical derivation and numerical analysis in Sections 2.2 and 3.1, respectively. This section demonstrates the equivalence again between the two at the experimental level. The experimental processes of offline VFRA and online VFRA are as follows:

**Offline VFRA:** The controllable harmonic power supply is used to apply sinusoidal currents with a frequency range of 1 to 1000 Hz, a frequency step of 1 Hz, and a constant amplitude of 125 A to the winding. The offline VFRA is obtained.

**Online VFRA:** Simulating the actual operating situation of the in-operation converter transformer, the measured harmonic current $i_N$ is loaded on the test converter transformer winding.

The VFRFs obtained by experimental method for offline VFRA and online VFRA at different measuring points are
shown in Fig. 6.

As shown in Fig. 6, the VFRFs at different measuring points are different due to the discrepancy in the modal characteristics of each position of the winding [28]. For the same measuring point, the VFRF trace of offline VFRA and online VFRA are consistent with the peak distribution. Therefore, only the VFRFs of the same measuring point can be compared to detect winding mechanical fault. Since offline VFRA has 1000 frequency points, the VFRF is smoother, with more peaks and troughs, and obvious variations. The online VFRA has only 20 frequency points, with large VFRF undulation.

To further compare the same frequency points, the VFRF of $k \times 100$ Hz frequency points in offline VFRA is also extracted, as shown in Fig. 7. Apparently, the VFRFs of offline VFRA and online VFRA have remarkably high consistency, with the same curve trace and variation trend, and the peaks and troughs correspond equally. However, it should be noted that offline VFRA requires the currents of constant amplitude. Limited by the output deviation from the controllable harmonic power supply, the offline VFRA inevitably suffers from a certain error, resulting in a discrepancy between the two. From the overall experimental results, offline VFRA and online VFRA have the same VFRF, which once again verifies the equivalence of the two. Moreover, compared with offline VFRA, online VFRA is not affected by current excitation and has higher stability.

4 | WINDING LOOSENESS CONDITION DETECTION BASED ON ONLINE VFRA

Due to the impact of harmonic current, the vibration of converter transformer winding is generally one order of magnitude higher or even greater than that of ordinary power transformer [29]. Under the action of long-term large vibration as well as complex magnetism, and high working temperature, the converter transformer winding is prone to mechanical fault such as looseness. The online VFRA is applied in this section to detect winding looseness fault.

4.1 | Effect of different factors on online VFRA

Due to changes in load and operating environment, etc., the windings of the in-operation converter transformer will flow currents of different magnitudes and varying harmonic content. Hence, it is necessary to study the influences of current amplitude and harmonic content on online VFRA. Similarly, experimental method is performed to simulate the above two scenarios.

**Scenario I:** The rated harmonic currents of 60%, 80%, 100% and 120% are applied to the winding.

**Scenario II:** The rated currents with harmonic content of 21.16%, 22.25%, 22.75% and 23.84% are applied to the winding.

Following the conventional FRA, two numerical indices are employed to quantify the effects of different factors on the online VFRA and also as evaluation indices for the subsequent winding looseness fault detection. They are the relative factor [9], [30], and the improved expectation [31, 32].
The relative factor is expressed as

\[ R_{text} = \begin{cases} 10^{-10} & \text{if } LR_{test} < 10^{-10} \\ 1 - \log_{10}(1 - LR_{test}) & \text{otherwise} \end{cases} \]  

(12)

where \( LR_{test} = C_{test} / \sqrt{D_{test}D_{ref}} \)

In laboratory experiments, a torque wrench was used to loosen the screws connecting the windings to excite winding looseness faults. The [actual torque/rated torque \times 100\%] is defined as the degree of winding looseness (degree of looseness). The torque at the factory of the converter transformer is regarded as the rated torque, i.e. 100% clamping pressure (CP). Two winding looseness faults were manufactured by loosening the screws with 95% torque (95% CP) and 90% torque (90% CP). Thus, three winding mechanical conditions of 100% CP, 95% CP and 90% CP were finally obtained.

The winding is loaded with the measured harmonic current \( i_{N} \) and the current signal and vibration signal are collected simultaneously to go for online VFRA. The offline VFRA is
also performed (the experimental procedure is the same as in section 3.3) to verify the efficiency of online VFRA. The VFRFs of offline VFRA and online VFRA at measuring point No. 9 under different CPs are shown in Fig. 9.

![Amplitude/(g/A²) Acceleration/(m/s²) vs Frequency/(Hz)](image)

Fig. 9. VFRFs of offline VFRA and online VFRA under different CPs (a) offline VFRA (b) online VFRA.

Fig. 9(a) and (b) represent the VFRFs of offline VFRA and online VFRA, respectively. Apparently, the trace and variation trend of the online VFRF and offline VFRF in the same condition are similar, which again verifies the equivalence of the two methods. The comparison of Fig. 9 with Fig. 8 illustrates that the VFRFs of offline VFRA and online VFRA change dramatically when there is a looseness fault in the winding. Within each frequency band, the peak of VFRF shows a trend of different degrees of leftward shift, reflecting the essential change of winding mechanical condition. Consequently, the trace variation of the VFRF can initially determine a mechanical fault in the winding. The above analysis shows that two methods can effectively identify the winding looseness faults. However, the offline VFRA has many problems such as transformer outage, tedious and time-consuming testing process, poor feasibility as well as extra equipment input, and has not been applied in the field yet. The online VFRA takes the actual harmonic current squared as the input and the winding vibration acceleration as the output, which realizes the online detection of VFRA. Moreover, the whole process is not time-consuming and does not require external equipment. Hence, the online VFRA has high application value and application prospect.

4.3 Comparison between online VFRA and different diagnosis methods

Further, online VFRA is compared with conventional FRA [11, 12], [32] and SCI methods [9] to demonstrate the sensitivity and detection capability of online VFRA for the winding mechanical fault. Similarly, two numerical indices, relative factor and expectation, are used to comprehensively evaluate the winding mechanical condition. Fig. 10 shows the FRFs of conventional FRA under different CPs. Table VI and Table VII shows the SCI values for different CPs.

From Fig. 10 and Fig. 9(b), compared with the significant variations in the VFRFs of online VFRA, the FRFs of conventional FRA under different CPs have a similar overall trace change pattern. Especially in the middle and high frequency bands, the FRF traces in the three conditions overlap and are almost identical. Therefore, the VFRF of online VFRA is more likely to reflect the winding looseness fault compared with the FRF of conventional FRA.

![Amplitude/(dB) vs Frequency/(kHz)](image)

Fig. 10. FRFs of conventional FRA under different CPs.

<table>
<thead>
<tr>
<th>CP (%)</th>
<th>Relative factor</th>
<th>Expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Online VFRA</td>
<td>FRA</td>
</tr>
<tr>
<td>95</td>
<td>0.388</td>
<td>3.086</td>
</tr>
<tr>
<td>90</td>
<td>0.153</td>
<td>3.150</td>
</tr>
</tbody>
</table>

**TABLE VI**

<table>
<thead>
<tr>
<th>CP (%)</th>
<th>SCI(Ω)</th>
<th>Change(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.153</td>
<td>0</td>
</tr>
<tr>
<td>95</td>
<td>0.153</td>
<td>0</td>
</tr>
<tr>
<td>90</td>
<td>0.153</td>
<td>0</td>
</tr>
</tbody>
</table>

As shown in Table III to Table V and Table VI, compared to the normal condition, the low frequency band relative factor of the online VFRA under winding looseness fault decreases substantially to below the threshold of 1.2, with a decrease of 67.67% and 87.25% for 95% CP and 90% CP, respectively. The expectation increases significantly to above the threshold of 0.2, and the expectation of 95%CP and 90%CP increased by 306% and 352%, respectively. Both indicate that the winding is loose. In addition, the relative factor gradually drops and the expectation progressively grows with the looseness degree. However, the low frequency band relative factors of the conventional FRA for the looseness faults are 3.086 and 3.150, which are much higher than the set threshold [30]; the expectation values are tiny. Finally, the conventional FRA diagnosed the winding mechanical condition as normal without identifying the winding looseness fault. Meanwhile, as shown in Table VII, the winding SCI value is 0.153Ω without any change, regardless of whether the winding is in normal condition or looseness fault. The SCI method also failed to identify the winding looseness fault. Therefore, compared with the traditional FRA and SCI method, the online VFRA proposed
in this paper has higher sensitivity and detection capability for winding mechanical fault, and is a better online monitoring method for winding mechanical condition.

The online VFRA evaluation results for all measuring points are shown in Fig. 11. The relative factor of all measuring points is less than the threshold. Of course, the average relative factor (0.147) of 90% CP is lower than the average relative factor (0.428) of 95% CP. The expectation of all measuring points is higher than the threshold. Correspondingly, the average expectation (0.716) of 90% CP is greater than the average expectation (0.577) of 95% CP. The above results illustrate that the relative factor and expectation can reflect the degree of winding looseness, i.e., the relative factor gradually drops and the expectation gradually grows as the degree of winding looseness intensifies. Therefore, the winding looseness fault can be initially determined by the trace variation of the VFRF, and relative factor and expectation can evaluate the winding looseness degree.

![Fig.11. Numerical indices at winding looseness fault for all measuring points](image)

Fig.11. Numerical indices at winding looseness fault for all measuring points (a) relative factor (b) expectation.

5 CONCLUSION

This paper proposes an online VFRA for winding mechanical condition detection using the harmonic currents unique to converter transformer. The main conclusions are as follows.

1. The online VFRF is deduced from the established winding vibration model, which is defined as the ratio of vibration acceleration to current squared.

2. It is proved that the online VFRA is consistent with the offline VFRA by numerical and experimental methods. The online VFRA is not affected by the current magnitude and harmonic content, and has high stability.

3. The online VFRA is only related to the winding mechanical condition, and the VFRF has changed significantly after the winding looseness fault. With the aggravation of the degree of looseness, the VFRF peak shifts to the left, the relative factor reduces, and the improved expectation grows. According to the variation patterns of VFRF trace and numerical indices, the winding looseness fault and the looseness degree can be identified.

The effectiveness of online VFRA has been verified in the laboratory experiments. However, the current signal and vibration signal of in-operation converter transformer are difficult to obtain simultaneously, so the field test is lacking. In the future works, we will develop a converter transformer current and vibration synchronization acquisition device, and apply the online VFRA proposed in this paper to monitor the winding mechanical condition.

REFERENCES


