Influence of Load Factors on Distribution Transformer Noise

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Abstract. Theoretical relations between load factors and distribution transformer noise are analysed. A 10kV/400kVA three-phase oil-immersed distribution transformer is used for sound pressure level test in various load conditions including various load ratios, unbalanced loads and power factors. The sound pressure levels of distribution transformer in different load conditions are compared and analysed. The results can be referenced for the field noise and vibration control of distribution power transformers.

1. Introduction

Distribution transformers are widely positioned near residential buildings. Unlike the high voltage main transformers, severe factors like over voltage, unbalanced load, heavy load and power factor are commonly found for distribution transformer. As the enhancement of environmental awareness of the inhabitants, the noise issue of distribution transformer is becoming the attention focus of the residents [1-2]. In order to control the distribution transformer noise in the neighborhood, the characteristics of transformers noise need to be investigated.

Transformer noise is the one of important problem concerned by transformer manufacturer and research institution around the world. Related researches are mainly focused on the noise characteristics of high voltage main power transformer with the voltage level over 110kV [3-8]. However, because of the limit of transformer load capacity and load conditions, the influence of load factors on the noise characteristics of distribution transformer is relatively few.

In this paper, a 10kV/400kVA three-phase oil-immersed distribution transformer is used for noise characteristic test in the conditions of over voltage, over load, unbalance load and reactive load. The relationship between load factors and sound pressure levels (SPLs) are analyzed. The test results can provide technical support for noise control of distribution power transformers.

2. Theoretical Relation Between Load Factors and Transformer Noise

2.1. The Relation Between Load Current and Transformer Noise

Assuming there are harmonic components to the load current, the transient load current $I(t)$ can be expressed by

$$I(t) = \sum_{i=1}^{N} I_i \sin(\omega_i t + \varphi_i)$$

(1)
where $N$ is the harmonic number of load current, $I_i$ and $\omega_i$ are the amplitude and angular frequency of the $i$th harmonic components.

The load current in the transformer windings generates a magnetic field that is proportional to the current density

$$\nabla \times \mathbf{H} = \mathbf{J}$$

(2)

$$\mathbf{B} = \mu_0 \mathbf{H}$$

(3)

$$B \approx \mu_0 NI / l$$

(4)

where $\mathbf{H}$ is magnetic field intensity, $\mathbf{B}$ is the magnetic flux density, $\mathbf{J}$ is the current density, $N$ is the number of the winding turns, $l$ is the winding length, $\mu$ is the relative permeability, $\mu_0$ is the permeability of free space.

The volumetric electromagnetic force in the windings can be expressed as

$$\mathbf{F}_m = \int_V \mathbf{f}_m dV$$

(5)

$$\mathbf{f}_m = \mathbf{J} \times \mathbf{B}$$

(6)

where $\mathbf{F}_m$ is the volumetric force vector, $\mathbf{f}_m$ is the electromagnetic force density, $V$ is the winding volume.

Assuming the phase of magnetic flux density is the same with load current [2], the winding electromagnetic force will be proportional to the square of load current [9].

$$F_m(t) \propto I^2(t) = \left( \sum_{i=1}^{N} I_i \sin(\omega_i t + \phi_i) \right)^2$$

$$= \sum_{i=1}^{N} \sum_{j=1}^{N} I_i \sin(\omega_i t + \phi_i) I_j \sin(\omega_j t + \phi_j)$$

(7)

2.2. The Relation Between Operating Voltage and Transformer Noise

The vibration of transformer core is caused by magnetostriction. The magnetic flux density in the core is expressed as

$$B = \frac{\Phi}{S} = \frac{U}{NS\omega} \cos \omega t$$

(8)

where $U$ is the voltage amplitude, $\Phi$ is the alternating magnetic flux, $S$ is the cross-section area of the core.

The micro-deformation of silicon steel sheet satisfies the following expression

$$\frac{1}{L} \frac{dL}{dH} = \frac{2e_0}{H_L^2} \left| \frac{H}{H_L} \right|$$

(9)
\[ \varepsilon = \frac{\Delta L}{L} = \frac{2\varepsilon_s}{H^2} \int_0^H |H| dH = \frac{\varepsilon_s U^2}{(NS\omega B_s)^2} \cos^2 \omega t \]  

(10)

where \( \varepsilon_s \) is saturation magnetostriction coefficient, \( H_c \) is the coercivity, \( L \) is the length of the silicon steel sheet, \( \Delta L \) is maximum deformation of silicon steel sheet, \( B_s \) is the saturated magnetic flux density. The vibration acceleration of transformer core can be expressed as [10]

\[ a = \frac{d^2 (\Delta L)}{dt^2} = -\frac{2\varepsilon_s LU^2}{(NSB_s)^2} \cos 2\omega t \]  

(11)

Thus, the magnetostriction force \( F_c \) is proportional to the square of transformer operating voltage.

\[ F_c \propto U^2 \]  

(12)

3. Transformer Noise Test and Analysis

3.1. The Relation Between Voltage and Transformer Noise

The transformer type is S13-M-400/10. Four noise measuring points are set around the transformer, as shown in Figure 1. The sampling frequency is 65536Hz.

Under the condition of balanced load, different voltages are applied to the transformer. Then, measure the sound pressure level of the transformer after it is stable. The test result is shown in Table 1. \( U_N \) is the rated voltage. Obvious increase of the transformer SPLs is observed with increasing voltage.

![Figure 1. Noise measurement points of the transformer.](image)
Table 1. SPLs of the transformer with different operation voltages

| Operating voltages | SPL / dB(A) |
|--------------------|-------------|
|                    | Point 1     | Point 2 | Point 3 | Point 4 |
| 50% $U_N$          | 30.0        | 29.3    | 30.6    | 29.5    |
| 70% $U_N$          | 32.9        | 30.5    | 33.8    | 30.7    |
| 90% $U_N$          | 37.3        | 39.6    | 37.9    | 35.8    |
| 95% $U_N$          | 38.5        | 40.9    | 39.2    | 36.6    |
| 100% $U_N$         | 41.5        | 41.9    | 42.2    | 41.7    |
| 105% $U_N$         | 47.3        | 46.3    | 48.9    | 50.9    |
| 110% $U_N$         | 55.4        | 55.9    | 56.7    | 58.8    |
| 115% $U_N$         | 61.2        | 61.9    | 62.8    | 62.3    |
| 120% $U_N$         | 68.5        | 67.4    | 69.5    | 69.8    |

3.2. The Relation Between Load Ratio and Transformer Noise

Under the condition of balanced load, different loads are applied to the transformer operating at rated voltage. The transformer SPLs in the conditions of different load ratios are shown in Table 2. The average SPL of 200% load ratio is 1.5 dB(A) higher than that of 50% load ratio.

Table 2. SPLs of the transformer with different load ratios

| Load ratio | SPL / dB(A) |
|------------|-------------|
|            | Point 1     | Point 2 | Point 3 | Point 4 |
| 50.0%      | 40.0        | 41.8    | 40.8    | 38.9    |
| 75.0%      | 40.0        | 41.7    | 40.8    | 39.6    |
| 100%       | 39.8        | 41.8    | 40.7    | 39.9    |
| 120%       | 39.7        | 42.0    | 40.1    | 39.8    |
| 140%       | 39.8        | 42.0    | 39.9    | 40.6    |
| 160%       | 39.8        | 42.1    | 39.8    | 41.5    |
| 180%       | 40.5        | 42.7    | 40.4    | 42.9    |
| 200%       | 40.6        | 43.5    | 41.2    | 43.8    |

3.3. The Relation Between Unbalanced Load and Transformer Noise

The loads of three phases are set to be unbalanced. In different operation conditions, the SPLs of the transformer are shown in Table 3. The differences of the averaged SPLs of various load unbalance conditions are not obvious.

Table 3. SPLs of the load-unbalance transformer

| Phase-A, -B and -C loads/ kVA | SPL / dB(A) |
|-------------------------------|-------------|
|                               | Point 1     | Point 2 | Point 3 | Point 4 |
| 100, 100, 0                  | 39.9        | 41.6    | 40.4    | 40.8    |
| 100, 0, 100                  | 39.4        | 41.1    | 40.5    | 39.3    |
| 0, 100, 100                  | 40.5        | 41.8    | 40.6    | 38.0    |
| 100, 100, 200                | 39.9        | 43.0    | 41.2    | 39.6    |
| 100, 200, 100                | 40.8        | 42.9    | 40.7    | 41.3    |
| 200, 100, 100                | 39.5        | 42.0    | 40.8    | 40.4    |

3.4. The Relation Between Power Factor and Transformer Noise

Unlike the previous conditions, reactive loads are applied to the transformer. In different load capacities, the SPLs of the transformer are shown in Table 4. The differences of the averaged SPLs of various reactive load conditions are not obvious.
Table 4. SPLs of the transformer with various power factors

| Reactive load ratio | SPL/ dB(A) |
|---------------------|------------|
|                     | Point 1    | Point 2    | Point 3    | Point 4    |
| 12.5%               | 41.3       | 41.7       | 41.8       | 40.0       |
| 37.5%               | 40.4       | 41.9       | 41.0       | 39.5       |
| 50.0%               | 41.3       | 41.7       | 41.9       | 39.9       |
| 62.5%               | 40.3       | 42.0       | 41.0       | 40.0       |

4. Conclusion
In this paper, the theoretical relation between load factors and transformer noise is analyzed. Noise tests are carried out on a 10 kV 400kVA oil-immersed distribution transformer. The influences of voltage, load ratio, unbalanced load and power factor on transformer SPLs are obtained. The following conclusions can be drawn:

1) The operation voltage has large influence on oil-immersed distribution transformer.
2) Compared with operation voltage, the influences of load factor, unbalance load and power factor on distribution transformer noise is not obvious.

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