Suppression Method of Vibration and Noise for Power Transformer Using Tuned Mass Damper

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Abstract. The vibration of operating power transformer may generate serious noise to affect the surrounding residents. In this paper, a 35kV oil-type transformer is chosen to study the suppression method of vibration and noise using tuned mass damper (TMD). Firstly, a finite element model of the transformer system with TMD is established. Comparisons of dynamic response and sound pressure level analysis for the transformer before and after installing TMD are carried out. Overall deformation distribution comparison shows that the vibration of each peak region on the surface of the original transformer box is suppressed obviously. After the vibration reduction using TMD, the maximum sound pressure level is reduced by more than 1 dB (A). The maximum noise reduction effect of the TMD is close to 1.6 dB (A), and the minimum noise reduction effect is more than 1 dB (A) at a distance of 1 m from the center of the transformer.

1. Introduction

Power transformer is one of the key equipment of power transmission system. Its function is not only to enhance the voltage to deliver the electric energy to the electricity utilization area, but also reducing the voltage to the use voltage at all levels to meet the power consumption demands. So some of the transformers are installed in the vicinity of the residential environment, especially some low voltage class transformers, such as 10kV or 35kV power transformers. It may bring about a problem of noise pollution to surrounding residents. As is know, if someone is exposed to high noise pollution environment for a long time, chronic harm will be brought to the human body, such as mild ear pain, nervous breakdown and so on. As a result, transformer vibration and noise control has become one of the research hotspots in recent years.

The causes of transformer vibration mainly include two aspects: core vibration leaded by magnetostriction and winding vibration leaded by load current leakage [1]. Generally, the vibration control of distribution transformer is mainly divided into two methods: vibration source control and propagation way control. The former adopts the way of improving the material and structure of the transformer itself, which can directly reduce the source vibration, and the effect is the most remarkable. But this method has high technical demand and cost. The second vibration reduction method is to apply isolation/absorption materials or equipment to absorb the energy of vibration signal in the process of vibration propagation, which has good vibration isolation effect and universality. The
propagation way control of transformer vibration is carried out mainly by the vibration isolation of the body, the vibration isolation of the foundation and the vibration absorption of the oil tank surface. In this paper, we use tuned mass damper (TMD) to reduce the vibration of a 35kV transformer. Compared with other damping devices, TMD is widely used because of its simple structure, reliable operation, strong corrosion resistance and long service life. The main work of this paper includes:

Modal and harmonic response analysis is carried out to obtain the modal frequency and corresponding vibration mode of the transformer model, as well as the dynamic response of the structure under simple harmonic load at each frequency, and to determine the resonant components of the transformer; (2) Through modal analysis and harmonic response analysis, the design parameters of TMD are determined, and the design scheme of transformer-TMD system is constructed; (3) The dynamic response of transformer and the sound pressure level of sound field are compared and analyzed, and the effect of vibration reduction and noise reduction is evaluated.

2. Theoretical Analysis of Vibration Control Using TMD

TMD is an auxiliary vibration-damping device with an additional structure, which is composed of a mass block, a spring and a damper, and is generally supported or hung on the main vibration system by a spring and a damper to form a vibration system containing the TMD. When the system is subjected to external load to generate vibration, the TMD is vibrated with the main vibration system through the connecting device, thereby generating energy to react with the main vibration system through the inertia force to consume the kinetic energy of the main vibration system and realize the purpose of vibration suppression [2].

The vibration system containing the TMD is abstracted as a model composed of elements of mass, stiffness and damping components, as shown in Fig.1. $M$, $K$, $C$ are the mass, stiffness and damping coefficient of the main vibration system and $m$, $k$, $c$ are the mass, stiffness and damping coefficient of the TMD.

![Figure 1. Vibration system model](image1)

![Figure 2. Model of 35kV oil-filled transformer](image2)

When there is a sinusoidal excitation load in the main vibration system, the motion of the system can be expressed by Equation (1).

$$
\begin{pmatrix}
M & 0 \\
0 & m
\end{pmatrix}
\begin{pmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{pmatrix} +
\begin{pmatrix}
C + c & -c \\
-c & c
\end{pmatrix}
\begin{pmatrix}
\ddot{x}_1 \\
\ddot{x}_2
\end{pmatrix} +
\begin{pmatrix}
K + k & -k \\
-k & k
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2
\end{pmatrix} =
\begin{pmatrix}
F e^{i\omega t} \\
0
\end{pmatrix}
$$

(1)

Where, $x_i = X_i e^{i\omega t}$, $i = 1, 2$. 

According to the extended fixed point theory [3], the steady state response of the main vibration system is taken as the design objective, and the above equation is solved to obtain the design conditions of the TMD:

\[
\gamma_{opt} = \frac{\omega_n}{\Omega_n} = \frac{1}{1 + \mu} 
\]

(2)

\[
\xi_{opt} = \frac{c}{2m\Omega_n} = \sqrt{\frac{3\mu}{8(1 + \mu)^3}}
\]

(3)

Where,

\( \Omega_n \) is the natural frequency of main vibration system, \( \mu \) is the mass ratio of TMD to main vibration system, \( \mu = m/M \).

\( \gamma_{opt} \) is the optimal natural frequency ratio of TMD to main vibration system, the equation (2) is called the optimal tuned condition.

\( \xi_{opt} \) is the optimal damping coefficient ratio of TMD to main vibration system, the equation 3 is called the optimal damping condition.

The design formula of TMD with mass ratio \( \mu \) as parameter is derived according to the above optimal conditions.

(1) The mass coefficient of TMD:

\[ m = \mu M \]

(4)

(2) The stiffness coefficient of TMD:

\[ k = m\Omega_n \left( \frac{1}{1 + \mu} \right)^2 \]

(5)

(3) The damping coefficient of TMD:

\[ c = 2m \sqrt{\frac{3\mu\Omega_n}{8(1 + \mu)^3}} \]

(6)
3. Finite Element Modeling of Transformer Structure

3.1. Transformer geometry and material properties

Taking a 35kV oil-filled power transformer as the research object, the three-dimensional geometric model is shown in Figure 2. The oil tank is a cuboid box with a cylindrical breather at the top, some high and low voltage wiring terminals packaged by insulated porcelain bushing are installed at the top of the tank cover, and a strip steel structure as the supporting base at the bottom, which is fixed with the foundation through bolts.

The material of transformer box is Q234, the elastic modulus 206 Gpa, the Poisson's ratio 0.28, the yield limit is 234 Mpa. The density is 7850 kg/m³. The material of insulated bushing is ceramic, the elastic modulus is 390 Gpa, Poisson's ratio is 0.26, and the density is 2700 kg/m³.

3.2. Finite model of transformer

The finite element method is a useful numerical technique for solving the approximate boundary value of partial differential equations. It is widely used as an effective engineering analysis method [4]. Grid division is an important link in the establishment of finite element calculation model. The grid quality of the model has a great influence on the calculation accuracy and convergence speed. In this paper, the intelligent partition method is used to divide the grid of the transformer box, and the grid size is constrained at the same time. After several verification of grid independence, it is determined that the global grid size constraint of transformer is 0.005 m, the number of grid is 238000, and the finite element calculation model is shown in Figure 3.

4. Design of TMD

The periodic vibration of 100Hz due to the magnetostriction of the core is the main frequency component of the load acted on the transformer box, which is also the main cause of the noise generated by the transformer. The dynamic response of transformer box is studied by modal superposition method. The dynamic load caused by magnetostriction is simplified as the excitation load applied to the upper and lower supports of the inner wall of the box in the opposite direction. Firstly, the modal frequencies and corresponding vibration diagrams of the transformer box are calculated. The frequency range of the first 30 modes is 18.138 Hz~131.28 Hz, and the frequency range of order 21 to order 26 is 85 Hz~115 Hz, which is near to 100 Hz, are easily been excited to local resonance for the transformer. Secondly, harmonic response analysis is carried out for the transformer box to decide the number and location of TMD.

Considering the contribution of each order mode, the harmonic response analysis of the bottom load of the box near 100 Hz and the geometric structure of the transformer, the TMD is designed for the transformer model. The installation position of distributed TMD is shown in Figure 4.

In order to reduce the influence of the transformer mode and to prevent the modal coupling of the TMD, it is appropriate to choosing the relative small quality on the premise of without reducing the
effect of the vibration and noise suppression of the distributed TMD. Synthesizing the number of distributed TMDs in the above layout scheme, multiple trial calculations are carried out, and it is finally determined that the mass of a single TMD is 0.98 kg, the stiffness coefficient is 384950 N/m, and the damping coefficient is 42.1 Ns/m.

5. Analysis of Application Effect of TMD

5.1. Dynamic Response of Transformer under the Action of TMD

Overall deformation distribution comparison of the original transformer and the transformer-TMD system under 100 Hz excitation has been carried out as show in Figure.5. It can be seen that the vibration of each peak region on the surface of the original transformer box is suppressed obviously, and the vibration kinetic energy produced by the transformer box is absorbed by each TMD. The vibration at the short side surface of the box is suppressed most obviously, and the surface deformation is less than 0.03 mm.

![Figure 5. Overall deformation comparison of transformer with/without TMD](image)

5.2. Analysis of Noise Reduction Performance of TMD

In this section, the harmonic analysis of sound field of the original structure of 35 kv transformer and the transformer-TMD system are studied. The radius of the surrounding medium is 1.8 m, and the medium is air. Without considering the internal situation, only the vibration and noise of the transformer oil tank are considered. Therefore, there is no medium in the oil tank. Verified by grid independence calculation, the total grid quantity of finite element model in acoustic field is about 1950000. The finite element model is shown in Figure.6 and the fluid in the field is air at 22 °C.

![Figure 6. Finite element model of acoustic field](image)
Figure. 7 shows the comparison of the standard sound pressure level cloud diagram of a weighted frequency band between the original transformer and the transformer with TMD. The figure shows that the maximum sound pressure level is located on the surface of the transformer. After the vibration reduction using TMD, the maximum sound pressure level is reduced by more than 1 dB (A).

![Sound pressure level cloud diagram](image)

**Figure. 7.** Sound pressure level cloud diagram of a weighted frequency band of transformer without/with TMD

Figure. 8 shows the distribution curve of the standard sound pressure level of 1 m far field around the transformer. It can be seen that the maximum noise reduction effect of the TMD is close to 1.6 dB (A), and the minimum noise reduction effect is more than 1 dB (A) at a distance of 1 m from the center of the transformer.

![Distribution curve](image)

**Figure. 8.** Curve of the standard sound pressure level of 1 m far field around the transformer
6. Conclusion
In this paper, a 35kV oil-type transformer is chosen to study the suppression method of vibration and noise using TMD. A finite element model of the transformer system with TMD is established. Comparisons of dynamic response and sound pressure level analysis for the transformer before and after installing TMD are carried out. Overall deformation distribution comparison shows that the vibration of each peak region on the surface of the original transformer box is suppressed obviously. After the vibration reduction using TMD, the maximum sound pressure level is reduced by more than 1 dB (A). The maximum noise reduction effect of the TMD is close to 1.6 dB (A), and the minimum noise reduction effect is more than 1 dB (A) at a distance of 1 m from the center of the transformer.

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