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# Study on Mechanical Properties of Friction Pendulum Isolation Device for Transformer

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# Study on Mechanical Properties of Friction Pendulum Isolation Device for Transformer

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**Abstract**—Electrical equipment has high vulnerability under strong earthquakes due to its own material and structure characteristics. The seismic performance of electrical equipment can be effectively improved by installing isolation devices. Based on the finite element simulation, this paper establishes the finite element simulation model of the friction pendulum isolation device suitable for the main transformer electrical equipment, calculates and compares the mechanical response of the isolation device under different design parameters. The results show that the friction pendulum isolation device with conventional design can meet the load-bearing requirements of the main transformer under conventional conditions; increasing the friction coefficient can effectively improve the energy dissipation effect of the friction pendulum isolation device, but the increase of the friction coefficient will limit the design displacement of the isolation device, and the specific isolation effect needs to be further evaluated; changing the curvature radius of sliding surface has little effect on energy dissipation of friction pendulum isolation device. The research results in this paper can provide research basis for the application of friction pendulum isolation device in the field of electrical equipment.

## 1. Introduction

Earthquake is the most destructive natural disaster on land, which will bring serious damage to operation of power grid. In recent years, earthquakes have caused significant losses to power facilities in China and abroad[1-3]. In 1999, the Chiji earthquake in Taiwan caused power outage in the north of Zhanghua ; Wenchuan earthquake in 2008 caused more than 200 substations to fail, resulting in direct economic losses of more than 12 billion yuan[4]. 110 kV Jiuzhai Substation Power Loss Caused by the 2017 Jiuzhaigou Earthquake[5].

Due to insulation requirements, electrical equipment casing and other components are mostly made of porcelain materials with low strength. At the same time, most of the electrical equipment bushings are high-rise and upright, and the root bending moment is large under earthquake, which make the seismic vulnerability of bushing is high. Once the function failure is caused by earthquake, it will bring serious direct and indirect losses.

The main transformer is the core electrical equipment in substation. The porcelain bushing is a high-rise structure and is the seismic vulnerability component of the equipment. At the same time, due to the amplification effect of the transformer body on the seismic action, its seismic response is further amplified.

Isolation design reduces the seismic response of superstructure by setting isolation layer composed of isolation device to absorb and consume seismic energy. For the isolation design of electrical equipment, relevant researchers have carried out research. In 1998, Bellorini et al. carried out finite element analysis of 230/150kV transformer and obtained its seismic response[6]. In 2003, Fujita Satoshi et al. installed friction pendulum isolation device on electrical equipment, and carried out experimental and numerical analysis[7]. In 2006, Murota et al. installed sliding bearings, rubber bearings and high damping rubber bearings below the transformer to verify the effectiveness of the isolation device for electrical equipment[8]. In the same year, Cao et al. put forward the applicability of the smooth discontinuous system of nonlinear restoring force composed of mass-spring to electrical equipment[9]. In 2009, Lu et al. conducted seismic and isolation analysis of isolated switchgear[10]. In 2011, Nacamuli et al. verified the applicability of the ball isolation device to the electrical cabinet by comparing the seismic response of the equipment before and after the installation of the isolation device[11].

Although some progress has been made in related research, the research on the mechanical properties of the friction pendulum isolation device applied to electrical equipment is still insufficient. In this study, the numerical model of the friction pendulum isolation device suitable for the main transformer electrical equipment is established, and the static loading analysis and horizontal displacement loading analysis are carried out respectively to obtain the mechanical response of the key parts of the equipment.

## 2. Basic theory of friction pendulum isolation device

### *2.1. Introduction of friction pendulum technology*

Galileo found that the pendulum is isochronous in 1582 : the pendulum swing cycle is related to the pendulum length, and has nothing to do with the quality of the pendulum. Accordingly, Zayas et al. put forward the friction pendulum isolation technology in 1985. The main principle is to extend the natural vibration period of the structure by the pendulum principle so as to avoid the characteristic period of the seismic wave. At the same time, the friction energy consumption in the process of reciprocating sliding of the spherical surface consumes the input energy of the seismic wave to the upper structure, controls the seismic response of the structure and reduces the destructive force of the seismic wave. In the process of earthquake, the friction pendulum isolation device connects the upper structure through the slider, so that the upper structure always maintains a horizontal state during the earthquake. After the earthquake, the friction pendulum isolation device automatically resets by its own gravity, so as to improve the efficiency of maintenance and reinforcement after the earthquake, and make the upper structure recover its normal function as soon as possible. The friction pendulum isolation device mainly includes upper support plate, slider, PTFE plate, lower support plate and limit device.

### *2.2. The restoring force model of friction pendulum isolation device*

The friction pendulum isolation device studied in this paper is a single pendulum. The isolation device has only one sliding surface at the lower support plate, so the isolation device can be simplified as a single pendulum motion of the slider moving along the arc surface of the lower support. The simplified mechanical model of the isolation device is shown in Figure 1 :

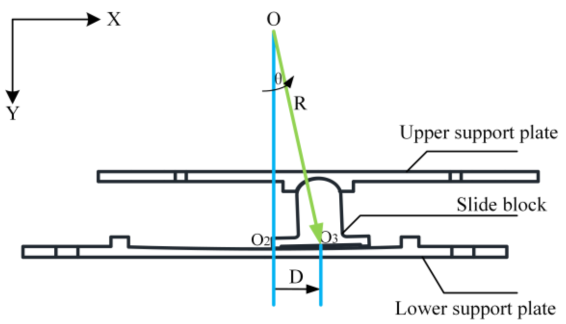


Fig 1 Mechanical model of friction pendulum isolation device

The horizontal restoring force, gravity and friction force of the friction pendulum isolation device are balanced at the center O. The equilibrium equation is as follows :

$$FR\cos\theta = WD + fR \tag{1}$$

$$f = \mu W\cos\theta \tag{2}$$

In the formula :

*F*-Horizontal response; *R*-Spherical radius of support plate under friction pendulum; $\theta$-Sliding angle of slider; *W*-Vertical load of isolation device; *D*-Horizontal sliding displacement; *f*-Friction force at the bottom of slider; $\mu$-Dynamic friction coefficient of slider bottom.

When $\theta$ is very small, $\cos\theta$ is approximately equal to 1, then Equation 1 can be simplified as :

$$F = \frac{WD}{R} + \mu W \qquad (v > 0) \tag{3}$$

$$F = \frac{WD}{R} \qquad (v = 0) \tag{4}$$

$$F = \frac{WD}{R} - \mu W \qquad (v < 0) \tag{5}$$

In the formula :

*v*-Velocity.

It can be seen from Formulas 3 to 5 that the restoring force of the friction pendulum isolation device can be approximately regarded as the sum of the restoring force part related to the moving displacement and the restoring force part related to the friction.

## 3. Numerical model of friction pendulum isolation device

### *3.1. Model parameters*

Based on the preliminary investigation and combined with the actual seismic resistance of electrical equipment, the preliminary design of pendulum friction isolation device is shown in Figure 2, in which the design sliding displacement is ± 100 mm.

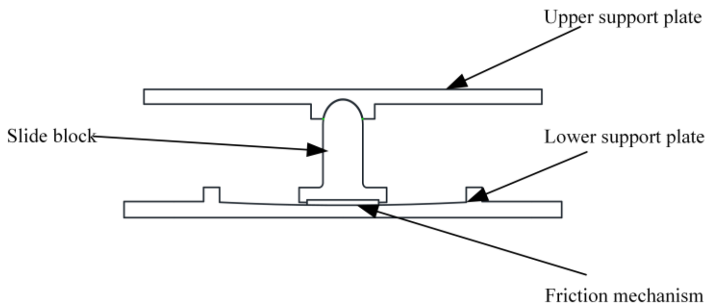


Fig 2 The figure of pendulum friction isolation device

The geometric dimensions of each component are shown in Table 1.

Table 1 Geometric parameters of finite element model of pendulum friction isolation device

| Component | Parameter | Size(mm) |
|---|---|---|
| Upper support plate | Plane size | 500×500 |
| | Thickness | 15 |
| Lower support plate | Plane size | 600×600 |
| | Thickness | 15 |
| | Curvature radius of sliding surface | 4000 |
| Slide block | Height | 150 |
| Friction mechanism | Plane size | Φ90 |
| | Thickness | 10 |

The steel and wear resistant materials in the model are regarded as ideal linear elastic materials, and the material parameters of each component are shown in table 2.

Table 2 Material parameters of finite element model of pendulum friction isolation device

| Component | Material | Density (kg/m3) | Elastic Modulus (GPa) | Poisson 's Ratio | Yield Strengt (MPa) |
|---|---|---|---|---|---|
| Upper support plate | Q345 | 7800 | 210 | 0.3 | 345 |
| Lower support plate | Q345 | 7800 | 210 | 0.3 | 345 |
| Slide block | Q345 | 7800 | 210 | 0.3 | 345 |
| Friction mechanism | polytetrafluoroethylene | 200 | 0.3 | 0.42 | — |

The ANSYS numerical model of friction pendulum isolation device is established as shown in figure 3.

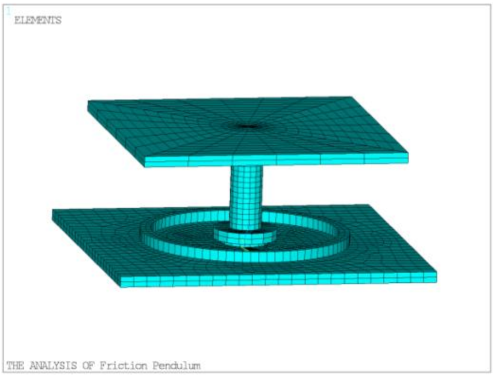


Fig 3 Numerical model diagram of pendulum friction isolation device

The model includes 8491 elements and 10561 nodes.

*3.2. Boundary condition*

The bottom of the isolation device is connected with the foundation of the electrical equipment, and the simulation is carried out in the form of node fixed connection, that is, the translational and rotational degrees of freedom in three directions are set to 0. The friction mechanism and sliding mechanism are set as bonding constraints ; according to the normal working state and the seismic state of the isolation device, the upper connection plate is subjected to surface load. At the same time, in order to ensure the overall translational motion of the upper connection plate, the rotational freedom of the four edges is restricted.

The upper and lower support plates of the isolation device contact with the upper and lower sliding surfaces of the sliding mechanism respectively. The contact surface has the characteristics of not penetrating each other, transferring normal pressure and friction force, not transferring tension, and has a highly nonlinear state. In the ANSYS modeling process, the contact surface is set according to the rigid-flexible contact, in which the contact area of the upper and lower connecting plates is set as the rigid target surface and simulated by TARGE170 element. The contact area of the sliding mechanism is set as a flexible contact surface, which is simulated by CONTA174. The sliding factor of the contact surface of the friction mechanism is set to 0.1.

*3.3. Loading*

In order to verify the mechanical response of the friction pendulum isolation device under static load and the hysteresis performance under static and displacement loads, the design applied conditions are as follows :

(1) Application of static load; (2) Application of displacement load

The loading conditions are set as follows :

Condition 1 :

Model parameter setting : friction coefficient of sliding surface is 0.05,0.1,0.15.

Step 1:Apply 0.1MPa load on the upper surface of the connecting plate to ensure that the next calculation can converge and complete the analysis successfully; Step 2:Apply 1MPa load on the upper surface of the upper connecting plate to complete the maximum vertical load ; Step 3:The vertical load applied in step 2 is transferred to step 3, and the horizontal displacement cyclic load is applied on the upper connecting plate, the amplitude is ± 100 mm, and the average speed is 100 mm/s.

Condition 2 :

Model parameter setting : the curvature radius of sliding surface of lower connecting plate : 3000mm, 4000mm, 5000mm.

Analysis step 1:the same as condition 1;Analysis step 2:the same as condition 1; Analysis step 3:the same as condition 1.

## 4. Analysis results

### *4.1. Results of static analysis*

Under static load, the stress nephogram of each component of the isolation device is shown in figure 4 –7.

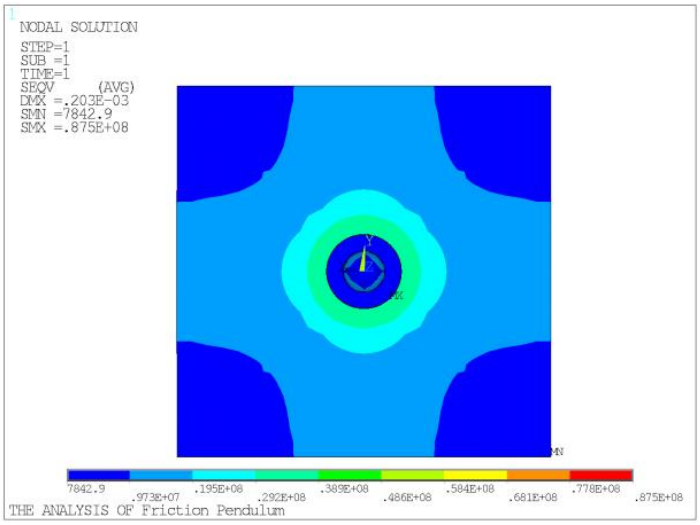


Fig 4 Stress nephogram of upper support plate

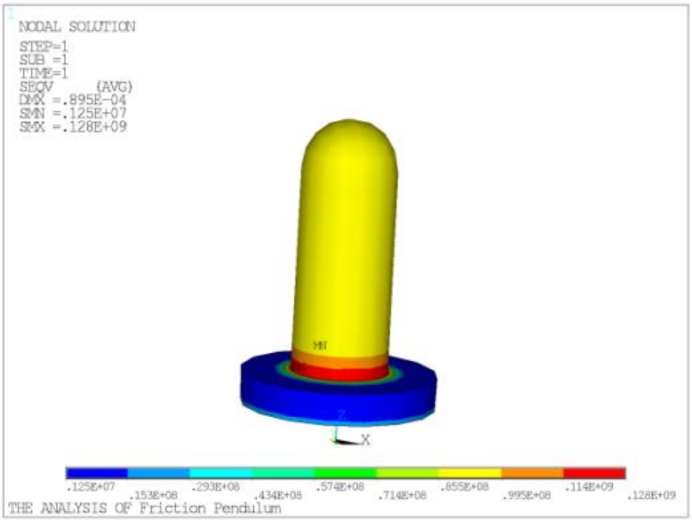


Fig 5 Stress nephogram of Slide block

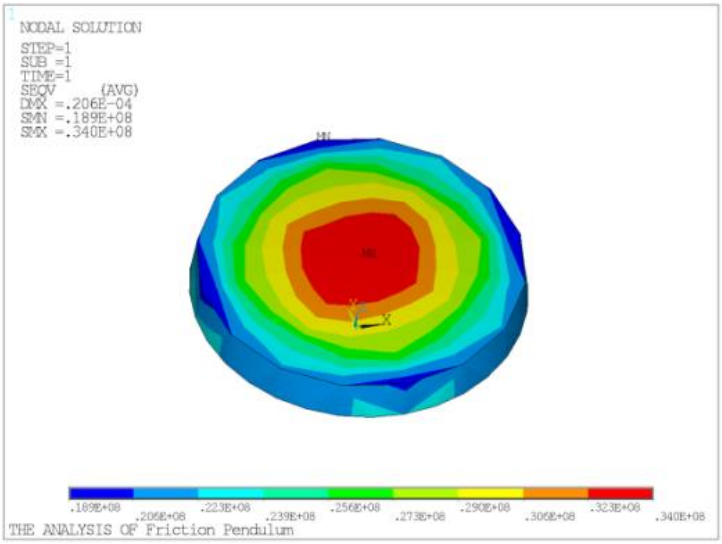


Fig 6 Stress nephogram of Friction mechanism

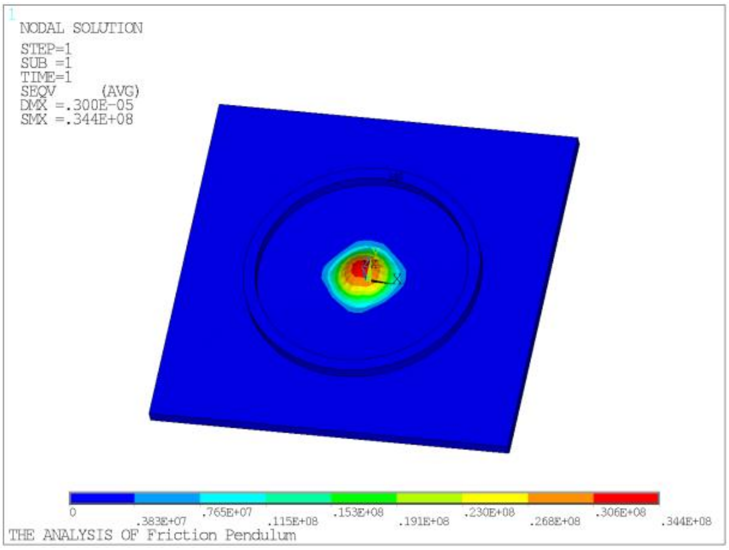


Fig 7 Stress nephogram of Lower support plate

It can be seen from Fig. 4 that under static load, the maximum stress of the friction pendulum isolation device appears in the upper connecting plate, and the maximum stress is 87.5 MPa. Considering that the yield strength of Q345 material is 345 MPa, the overall minimum stress safety margin of the structure reaches 3.94 times.

### *4.2. Displacement load analysis results*

Under the action of displacement load, the energy dissipation hysteresis curve of isolation device in condition 1 and condition 2 is shown in figure 8-9.

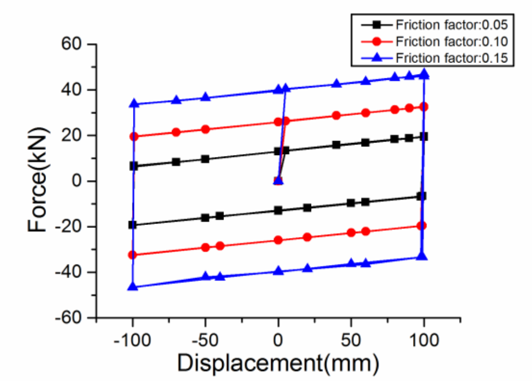


Fig 8 energy dissipation hysteresis curve of isolation device with Different Friction factors

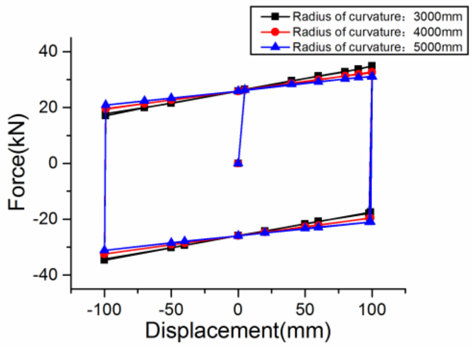


Fig 9 energy dissipation hysteresis curve of isolation device with Different radius of curvature

Comparing Fig. 8 and Fig. 9, it can be seen that compared with the curvature radius, the influence of friction coefficient on the energy dissipation effect of isolation device is more obvious. It is more economical and reasonable to adjust friction coefficient to influence energy dissipation effect of isolation device.

## 5. Conclusion

In this paper, through the static analysis and displacement load analysis of the friction pendulum isolation device used for transformer electrical equipment, the conclusions are as follows :

(1) According to the layout of eight isolation devices in a single 220kV main transformer, the strength of each component of the isolation device meets the design requirements, and the stress safety margin is large.

(2) Increasing the friction coefficient can effectively improve the energy dissipation effect of the friction pendulum isolation device, but the increase of the friction coefficient will also limit the design displacement of the isolation device ;

(3) Changing the curvature radius of the sliding surface has little effect on the energy dissipation of the friction pendulum isolation device.

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