Structural Analysis and Optimization of Steel Pin on Cylindrical Head Suspension Porcelain Insulators

Hua Xu\textsuperscript{1}, Yangyang Zhou\textsuperscript{1}, Jungang Yin\textsuperscript{2*}, Ruiqing Zhang\textsuperscript{3}, Chao Li\textsuperscript{4}, Senlin Wang\textsuperscript{5} and Fuming Yi\textsuperscript{5}

\textsuperscript{1} State Grid Zhejiang Electric Power Co., Ltd., Hangzhou, Zhejiang, 310007, China
\textsuperscript{2} College of Electrical and Information Engineering, Hunan University, Changsha, Hunan, 410082, China
\textsuperscript{3} College of Electrical Engineering, Zhengzhou University, Zhengzhou, Henan, 450001, China
\textsuperscript{4} Jiangsu JS Electric Hardware Co., Ltd., Yangzhou, Jiangsu, 225200, China
\textsuperscript{5} HDHL Electrical and Information Tech. Co., Ltd., Changsha, Hunan, 410205, China
Email: jg_yin@hnu.edu.cn

Abstract. There is no essential difference in theory between the inner and outer insulating properties of cylindrical and conical head disc suspension porcelain insulators. Compared with a conical head porcelain insulator, a cylindrical head porcelain insulator is significantly lighter in weight, which can effectively reduce the mechanical load of the tower and wire; and it has better dispersion and adjustment capabilities for changes in material properties over time, so that the product is not subject to excessive and uneven stress over a long-term. In order to improve the mechanical performance of cylindrical head insulator products, this paper establishes a parameterized fine simulation model of the steel pin without changing the geometry of the insulator iron cap and porcelain body. The finite element method is used to calculate and analyze how the geometric parameters of the steel pin influence insulator mechanical properties, which can provide design reference for further product optimization.

1. Introduction
In recent years, the deterioration rate of the transport disc suspended porcelain insulator is much higher than that can be neglected, which poses a serious threat to the stability of the nationwide power grid [1-2]. The deterioration of the operating insulator is the combined result of electrical, mechanical and environmental factors. At present, researchers have carried out a lot of studies on the mechanical performance assessment of porcelain insulators, involving deformation characteristics under static and dynamic load [3-4], vibration fatigue performance [5-6], ice fault rate [7], operation status assessment of large tonnage porcelain insulator [8] and comprehensive risk assessment of overhead transmission lines in extreme external environment [9].

The disc suspended porcelain insulators can be divided into two types, in terms of conical and cylindrical head shapes. Most of the suspension porcelain insulators used in overhead transmission lines in China are conical structures; however, the cylindrical head insulators have increased significantly during recent years. There is no essential difference between the cylindrical and conical head insulators, with respect to the inner and outer electrical insulation performance [10]. As for the mechanical properties, the conical head insulator is greatly affected by the temporal changes of component materials (cement adhesive, etc.), which is prone to changes of the structural matching or
large stress concentration. In contrast, a cylindrical head insulator has better dispersion and adjustment ability for the material temporal changes, significantly reducing its impact in the product with high reliability [11-12].

According to statistics, the manufacture quality is the main reason for the broken string of suspension porcelain insulators [13]. Given the technical cost, it becomes increasingly difficult to improve the performance of the component material itself; so the optimization of the insulator structure has become the key to enhancing product reliability. The cylindrical head insulator head structure has almost no conical angle, so the stress and strain can only be distributed as evenly as possible by optimizing the steel pin structure. It is very effective in optimizing the insulator structure by the finite element method (FEM) [14-15]. This paper establishes a fine simulation model of steel pin and analyzes the influence of its geometry on the mechanical properties of a cylindrical head porcelain insulator, hopefully providing design reference for product optimization.

2. Insulator Simulation Model
In this paper, a certain type of 160kN cylindrical head porcelain insulator is taken as a study case, of which the simulation model is shown in figure 1.

![Diagram of the simulation model of a certain cylindrical head porcelain insulator.](image)

\[
\begin{align*}
\nabla \cdot (FS)^T + F_v &= 0 \\
F &= I + \nabla u \\
S &= S_{ad} + J_iF_{inel}^{-1}(C : \varepsilon_{el})F_{inel}^{-T} \\
\varepsilon_{el} &= 2^{-1}(F_{el}^T F_{el} - I) \\
F_{el} &= FF_{inel}^{-1} \\
S_{ad} &= S_0 + S_{ext} + S_q \\
\varepsilon &= 2^{-1}[(\nabla u)^T + \nabla u + (\nabla u)^T \nabla u] \\
C &= C(E, \nu)
\end{align*}
\] (1)

The simulation is based on the solid mechanical equations as shown in (1), where \( F \) is deformation gradient, \( S \) is the second Piola-Kirchhoff stress, \( F_v \) is volume force, \( u \) is the displacement field, \( I \) is prestress, \( F_{inel} \) contributes to inelastic deformation gradient; \( J_i \) is inelastic volume ratio, \( \varepsilon \) is strain tensor, \( C \) is Cauchy-Green tensor, \( E \) is Young's elastic modulus, \( \nu \) is Poisson ratio and \( S_{ad} \) is prestress tensor. Considering the actual working conditions, the model needs to add fixed constraints to the
inner side of the iron cap head, and add the corresponding load to the insulator steel pin. The constraint equations are as follows:

\[
\begin{align*}
S \cdot n &= F_A \\
F_A &= \frac{F_{tot}}{A}
\end{align*}
\]

(2)

where \( n \) is boundary unit normal vector, \( F_A \) is boundary load, \( A \) is boundary area, and \( F_{tot} \) is total force and appears as follows:

\[
F_{tot} = \begin{bmatrix} 0 \\ 0 \\ -F_N \end{bmatrix}
\]

(3)

where \( F_N \) is the insulator rated load at 160 kN.

Relevant material parameters are set up in table 1.

| Material     | Elastic Modulus/Pa | Poisson's Ratio |
|--------------|--------------------|-----------------|
| Porcelain    | 7.63E10            | 0.16            |
| Cement       | 3E10               | 0.18            |
| Cork mat     | 1E9                | 0.43            |
| Iron cap     | 1.1E11             | 0.3             |
| Steel pin    | 2E11               | 0.3             |

### 3. Steel pin Geometric Parameters

![Figure 2. Diagram of the geometrical parameters of the insulator steel pin.](image)

This paper mainly investigates the influence of the head geometric parameters of a steel pin immersed in the cement adhesive on the mechanical properties of the insulators. As shown in figure 2, five major geometric parameters are selected for analysis, namely root arc radius R1, middle arc radius R2, top arc radius R3, pin head height D1 and pin head width D3.
4. Simulation and Discussion

4.1. Parametric Sweep of D3
Calculating the stress and strain distribution in porcelain, steel pin and cement by scanning parameter D3. Figures 3(a), (b) and (c) exhibits how the maximum stress and strain in porcelain, steel pin and cement change with D3; Figures 8(a) and (b) show the stress cloud map when D3 gets its minimum and maximum values, respectively; while figures 8(c) and (d) show the strain cloud map when D3 gets its minimum and maximum values, respectively.

Figure 3(a) indicates the maximum stress occurs in porcelain when D3 is around 17 mm, while the volume strain values remains very low over the sweep range. It can be seen from figures 3(b) that D3 has no obvious effect on maximum stress and volume strain on steel pin. Figure 3(c) reflects monotonic decreasing characteristic of both maximum stress and strain on the cement as D3 increases. From figures 8(a) and (b), it is found that the maximum stress point on porcelain head moves from the inner side of the bottom to the inner side of the top; however, figures 8(c) and (d) indicate that the maximum tensile strain point is always on the inner side of the cylindrical head top.

4.2. Parametric Sweep of D1
As shown in figure 4(a), there exists an optimized point between 19 and 20 mm in which the maximum stress on porcelain reaches its minimum. Figure 4(b) shows that D1 hardly influences on the force condition of the steel pin. Similarly to D3, monotonic decreasing characteristic can also be observed of both maximum stress and strain on cement as D1 increase.

Figures 9(a), (b), (c), (d) show that the maximum stress and strain points on porcelain will move upwards when the pin head increases in length; it causes stress concentration at the corner of the porcelain head if the pin head is too close to the inner side of the porcelain head.

4.3. Parametric Sweep of R2
Figure 5(a), (c) shows that the maximum stress and strain of porcelain and cement increase with R2 increases. Figure 5(b) shows that the change in R2 did not have significant effects on the maximum stress and strain of the steel pin.

Figures 10(a), (b) show that the maximum stress moves towards the foot of the cylinder and the strain distribution does not change greatly as R2 increases.

4.4. Parametric Sweep of R3
Figure 6(a) shows that the maximum stress on porcelain reaches its minimum when R3 is about 4 mm. Figure 6(c) reflects that the increase in R3 slightly reduces the maximum stress on cement. Similarly, figure 6(b) reflects that the change in R3 had no significant effect on the maximum stress and maximum strain of the steel pin.

Figures 11(a), (b) show that the maximum stress point in porcelain moves upwards to proximity to the steel pin, while the strain distribution in porcelain shown in figures 11(c) and (d) does not change significantly with R3.

4.5. Parametric Sweep of R1
From figure 7(a), it was found that the maximum stress on porcelain increases with R1, while the maximum strain changes slightly when R1 is small and increases rapidly when R1 exceeds 8 mm. Figure 7(c) shows that when R1 exceeds 3.6 mm, the maximum stress and maximum strain in cement will have a step rise, followed otherwise by a step drop when R1 exceeds 9 mm, which is followed by a step rise again when R1 exceeds 14.2 mm.

From figure 12(a), (b), (c) and (d), it is found that the change in R1 does not cause significant changes in the maximum stress and strain distribution on porcelain.
Figure 3. D3 Effect on maximum stress and strain of porcelain parts (a), steel pin (b) and cement (c).

Figure 4. D1 Effect on maximum stress and strain of porcelain parts (a), steel pin (b) and cement (c).

Figure 5. R2 Effect on maximum stress and strain of porcelain parts (a), steel pin (b) and cement (c).

Figure 6. R3 Effect on maximum stress and strain of porcelain parts (a), steel pin (b) and cement (c).

Figure 7. R1 Effect on maximum stress and strain of porcelain (a), steel pin (b) and cement (c).
5. Conclusion

In this paper, a parameterized fine model of a cylindrical head suspension porcelain insulator is established. The five major geometric parameters, namely root arc radius $R_1$, middle arc radius $R_2$, top arc radius $R_3$, pin head height $D_1$ and pin head width $D_3$, are swept for analysis before the following conclusions can be drawn:

1. $D_3$ and $D_1$ determine the head size of insulator steel pin and have great impact on the stress of insulator porcelain body; while $R_1$, $R_2$ and $R_3$ have relatively little impact on it, but the stress and strain distribution can be optimized to avoid excessive concentration;
(2) D3, D1 and R1 have great influence on the stress and strain of cement, while R2 and R3 have less impact on the stress and strain of cement;

(3) None of the five geometric parameters has a significant effect on the steel pin, and no obvious change rules are found.

The fine simulation model of cylindrical head porcelain insulator can provide a fast and reliable design reference for product optimization. Next, we will conduct further studies on the transient over-voltage and electro-mechanical co-simulations.

References
[1] Zhang T, Tian F, Wang Y J, et al. 2020)Analysis on a fracture fault of porcelain insulator tension string in 220 kV transmission line J. Insulators and Surge Arresters 6: 187–191.
[2] Yang W, Bai Y X, Hua K, et al. 2018 Investigation on the use of large tonnage insulators in uhv transmission lines J. Insulators and Surge Arresters 5: 241–247.
[3] Gao S, Liu Y, Huang Q, et al. 2020 Mechanical proper ties analysis of domestic large tonnage porcelain insulators based on operating load conditions Proceedings of 4th Information Technology, Networking, Electric and Automation Control Conference New York. pp. 289–294.
[4] Liu Y, Yuan T, Xu S D, et al. 2019 Study on stress-strain characteristics of cap and pin insulator under static load J. Insulators and Surge Arresters 6: 198–204.
[5] Yao X Y, Zhou J, Gu C, et al. 2018 Test and analysis on vibration fatigue properties of 840 kn large tonnage suspension insulator J. High Voltage Engineering 44(7): 2418–2423.
[6] Zhang R, Wu G Y, Yuan T, et al. 2009 The study of mechanical vibration characteristics of transmission line insulators string J. Insulators and Surge Arresters 1: 12–17.
[7] Huang H, Tan S, Zeng H R, et al. 2017 Icing failure rate model of transmission line based on real-time stress J. Journal of Electric Power Science and Technology 32(3): 145–152.
[8] Lu M, Gao C, Zou Q G, et al. 2021 Research on Operation state evaluation method of large tonnage porcelain insulator for uhv ac transmission line J. Proceedings of the CSEE 41: 1–9.
[9] Huang H, Lei J Z, Zeng H R, et al. 2019 Integrated risk assessment system of transmission line under extreme external environment J. Journal of Electric Power Science and Technology 34(2): 119–127.
[10] Cheng H Y, Lin R W 1994 Performance comparison of head structure of disk suspension insulators J. Insulators and Surge Arresters 5: 16–19.
[11] Zheng J 1996 Research of head structure of disk suspension insulators J. Insulators and Surge Arresters 4: 38–39.
[12] Zhou F X 1994 Reliability of cylindrical head suspension insulators J. Insulators and Surge Arresters 1: 9–12.
[13] Qiu Z B, Ruan X J, Huang D C, et al. 2016 Study on aging modes and test of transmission line porcelain suspension insulators J. High Voltage Engineering 42(4): 1259–1267.
[14] Gao J, Wang Y H 2011 The Influence of suspension insulator head structure to its electrical performance J. Insulators and Surge Arresters 1: 12–18.
[15] Gao J 2013 Structural optimization of cylindrical disk suspension insulator 2: 24–27.