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Theoretical Calculation of Ultimate Bearing Capacity and Fatigue of Safety Pin of Transmission Tower

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Abstract

In this paper, the hazard of normal operation power lines caused by transmission lines icing is analyzed. On the basis, several technology means of preventing the hazard of transmission lines icing in power grid in China are summarized. A new kind of overload protection fitting which is safety pin is designed in this paper, which can make transmission line dissociate from tower when ice thickness exceed the numerical value that ultimate load related. And then collapse of power transmission tower and disconnection of transmission are prevented and the goal of avoiding and decreasing the ice disasters is achieved. Ultimate bearing capacity of safety pin is researched based on elastic-plastic theory and elastic limit load and plastic limit load of safety pin are obtained. Finally, applying Palmgren Miner linear fatigue damage accumulation rule, fatigue life of safety pin is calculated.

Keywords:transmission line tower; safety pin; ultimate bearing capacity; fatigue

1.Introduction

In the early 2008's ice-and-snow disasters State Grid Corporation suffered serious damage. This ice-and-snow disaster caused direct property losses of 10.45 billion yuan and post-disaster reconstruction and rehabilitation need to invest 39 billion yuan[1]. In this ice-and-snow disasters, the number of tower collapses and damage in the 500KV transmission line in State Grid Corporation is respectively 506 and 142; 220KV is 821 and 239; 110KV is 1788 and 421; 35KV is 2305 and 1041.The loss of transmission line tower is so serious that influence to normal operation of transmission line is greatest and reconstruction is the most difficult.

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2.Methods of Preventing Transmission Lines Icing

Although now in the world the failure caused by ice-coating is unable to be prevented completely, through such measures as de-icing, on-line monitoring and anti-icing the degree of damage can be reduced effectively[2]. De-icing applies the measures of changing lines design and improving Line Design Criteria; ice Conditions monitoring applies the system of on-line monitoring to observe ice conditions of transmission line tower, conductors and insulator of remote areas in the control room; ice-melting applies technology of short-circuit currents. But the measures have many problems in the efficiency for the major natural disasters and effect and must continue to be researched. Researchers need to explore a new way to prevent disasters actively.

The research of design method preventing disaster actively and the exploitation of safety device controlled automatically in the transmission lines can reduce 90% of the loss in the design criteria, but construction investment is the same. The safety pin which is a kind of overload protection hardware can make transmission lines dissociate from towers to prevent tower collapses, reduce losses and repair quickly when ice thickness exceeds the numerical value that relates to the ultimate load.

3.Design of Safety Pin

The location of safety pin has great influence on tower-line separation, so various locations of insulator string should be calculated accurately and the position of the minimum strength is the location of safety pin. Taking into account repair the location which is stalled in the place of insulator string and over insulator string is inappropriate, because skirt edge of insulator string will be injured when string falling apart impacts with the ground. At last the location of safety pin is stalled in the place of hexagon head bolts with split pin hole on shank connecting shank linking socket-clevis eye and yoke plate, as shown in Figure 1. Selection of materials mainly depends on their strength and manufacturing technique etc and makes a great difference on dimension design of safety pin, so materials processing must be consistent with materials selected in the design drawings. This paper chooses materials for Q235. Safety pin plays a role in connection of hexagon head bolts with split pin hole and separation, so cross section makes a bit change in original cross section of hexagon head bolts with split pin hole, as shown in fig.2. Shank linking socket-clevis eye selects WS-16 and yoke plate selects L-1645-1. These two kinds of hardware can meet the size of design.

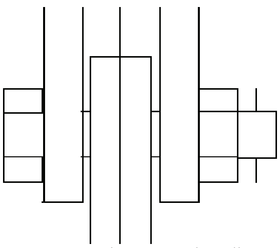

Fig.1 Location diagram

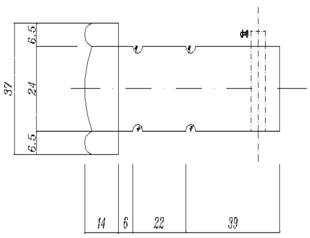

Fig.2 Schematic diagram

The safety pin is located in hexagon head bolts with split pin hole on shank linking socket-clevis eye and yoke plate. To make tower-line separation through strength failure of safety pin, mechanical behavior of safety pin is analyzed accurately and the value is equal to load of suspended string. Load of suspended string must be calculated accurately to ensure tower-line separation on occasion and work normally in other operating conditions. Load of suspended string is composition of vertical load and horizontal load of multiple conductors. Through calculation load of suspended string are 59702N, 46474 N and 56030 N in operating conditions of winds, the lowest temperature and broken-wire. The load of controlling tower-line separation which is 130KN can meet engineering requirements.

4.Analysis of Ultimate Bearing Capacity of Safety Pin

4.1.Calculation Model

Connection of safety pin is a loose connection and some gaps is between shank linking socket-clevis eye and yoke plate. So it is inappropriate that the connection is calculated by shear bearing capacity. The calculation must consider flexural strength and bending force is key. Calculation model of safety pin is shown in fig.3.The calculation model is simplified as simply supported beam under distributed load.

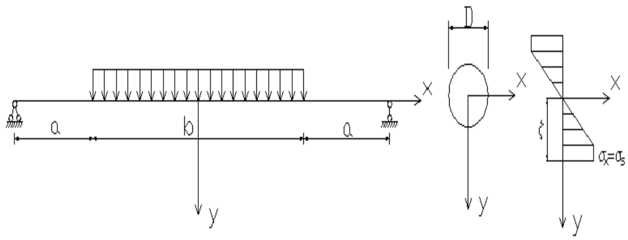

Fig.3 Diagram of calculation model

4.2.Calculation of Stress Concentration Factor

Under the load of controlling tower-line separation annular notch of safety pin produces stress concentration and then strength failure of safety pin occurs. So transmission line tower can be protected trough tower-line separation. Stress concentration factor of annular notch is calculated according to Formula 1[6].

$$K_t = [(1.0000 - 0.0027q + 0.0071q^2 - 0.0061q^3 + 0.0017q^4) + (0.1811 + 0.7584q - 4.7083q^2 + 6.382q^3 + 2.5358q^4)y - (5.0003 + 8.5836q - 76.5172q^2 + 105.4578q^3 - 42.8756q^4)y^2 (15.0157 + 26.2284q - 237.7754q^2 + 333.2765q^3 - 126.8873q^4)y^3 [K_t/K_{t,s}]_{r/a=0.6} K_{t,s} \quad (1)$$

Where, $q = r/a = 0.1905$, $y = 2t/D = 0.174$ is notch parameter, $[K_t/K_{t,s}]_{r/a=0.6} = 0.659183798$ and $K_{t,s} = 3.2508$ are stress concentration factor of special notch. Stress concentration factor (K_t) is calculated through Formula 1 and is 2.1.

4.3.Calculating Ultimate Bearing Capacity

Calculation model of safety pin is simplified as transverse bend of simply supported beam and belong to problem of plane stress. Stress component is:

$$\left.\begin{array}{l}\sigma_y = \sigma_z = \tau_{xy} = \tau_{yz} = \tau_{zx} = 0 \\ \sigma_x = \sigma\ (x, z)\end{array}\right\} \quad (2)$$

Formula 1substituted mathematical expression of misses yield condition: $\sigma = \sigma_s$ .Because safety pin exist stress component the yield condition of notch is:

$$\sigma = \frac{\sigma_s}{K_t} \tag{3}$$

The edge of safety pins first start the plastic deformation in the elastic stage and now safety pin is the elastic limit state. Elastic limit moment is:

$$M_e = \frac{1}{32}\pi d^3 \frac{\sigma_s}{K_t}$$

As the lead increases, the state of safety pin changes from elastic state to plastic flow state. Now the entire cross section of safety pin is in the yield state. Plastic limit moment is:

$$M_s = 4\int_0^{d/2} \sigma_x \cdot \sqrt{\left(\frac{d}{2}\right)^2 - y^2} \cdot y\mathrm{d}y$$

$$=4\int_0^{\xi} \frac{\sigma_s y^2}{\xi}\sqrt{\left(\frac{d}{2}\right)^2 - y^2}\mathrm{d}y + 4\int_{\xi}^{d/2} \sigma_s\sqrt{\left(\frac{d}{2}\right)^2 - y^2} \cdot y\mathrm{d}y$$

When $\xi = 0$, $M_s = \frac{1}{6}\frac{\sigma_s}{K_t}d^3$. The moment of notch is $M = \frac{1}{2}qab$. When $M = M_e$, safety pin is in the elastic limit state. Elastic limit load is:

$$q_e = \frac{\pi d^3 \sigma_s}{16 K_t ab} \tag{4}$$

When the load increases to certain value the entire cross section of safety pin is in the plastic state. Now the load is plastic limit load:

$$q_s = \frac{d^3 \sigma_s}{3 K_t ab} \tag{5}$$

Through calculation, $q_e = 3714.3N/mm$ $q_s = 6308.8N/mm$ .Changing into concentrated load: $F_e = q_e b = 67KN$, $F_s = q_s b = 114KN$ .When safety pin is in the elastic limit state safety pin turn into degree-of-freedom structure and loss capacity. After a bit load is increased safety pin fracture in the notch. So transmission line tower can be protected by the tower-line separation.

Through calculation load of suspended string are 59702N, 46474 N and 56030N in operating conditions of winds, the lowest temperature and broken-wire. They were less than the elastic limit load (67KN) and so safety pin meets the engineering requirements. Because the ultimate load which is calculated according to ideal elastic-plastic model is smaller the error of calculated value and the load of controlling tower-line separation can meet requirements.

5.Analyzing Fatigue of Safety Pin

Transmission line would vibrate differently because of the role of wind. The mechanical force of the vibration will pass to the safety pin and then fatigue damage of safety pin will occur after various alternating stress intensity reaches certain intensity. Fatigue life of safety pin is an important factor of designing safety pin and so this paper calculated fatigue life of safety pin.

5.1.S-N Curve of the Material of Safety Pin

To calculate fatigue damage of safety pin S-N curve need to be get. S-N curve of safety pin needs to be amended because section size and other factors of safety pin change. Based on least square method equation of S-N curve is obtained:

$$\lg Np = a_p + b_p \lg(K_{\sigma D}\sigma)$$

Where Np and σ are respectively stress level and cycles. Charles Machine Design Manual was: $a_p = 25.128$, $b_p = -8.547$. $K_{\sigma D} = \frac{K_\sigma}{\varepsilon_\sigma \beta_1}$ is fatigue strength reduction factor. $K_\sigma = \frac{K_t}{0.88 + AQ^b}$ is fatigue notch factor and ε_σ is size effect factor. β_1 is coefficient of surface processing. Through calculation, $\varphi = \frac{1}{6}$, $Q = 2.42857$. Look-up table was $b = 0.345, A = 0.336$. K_t is theoretical stress concentration factor. Look-up Charles Machine Design Manual was 2.8. Through calculation, $K_\sigma = 2.1$, $K_{\sigma D} = 2.5$. The modified S-N curve expression is:

$$\lg Np = 25.128 - 8.547\lg(2.5\sigma) \tag{6}$$

5.2.Theoretical Calculation of Fatigue Life

Requirements of designing of fatigue life are fatigue damage does not occur within a certain period of time. To estimate fatigue life the calculation must select accumulated damage criterion of fatigue besides S-N curve. This paper selects Miner linear cumulative damage criteria and its expression is:

$$D = \sum_{i=1}^{l} n_i / N_i = 1 \tag{7}$$

n_i are cycles corresponding σ_i, N_i are cycles of materials. When fatigue damage occur the total number of cycles is N:

$$N = 1 / \left[\sum \frac{\gamma_i}{N_i} \right] \tag{8}$$

γ_i is the percentage of circulating corresponding σ_i. The formula which estimates fatigue life is:

$$Y = \frac{N}{N'} \tag{9}$$

N is the total number of cycles and N' is number of cycles of the year.

Besides all static load of transmission line vibrating load includes dynamic load which has a certain frequency. In this paper, number of vibration of dynamic load is calculated as Weibull distribution which analyzes distribution parameters of wind speed. Wind speed range which cause aeolian vibration of transmission line is 0.5～10m/s. Frequency range of vibration of transmission line, which is calculated according to the project parameters, is between 3Hz～75Hz. In the practical calculation, frequency range of vibration of transmission line is divided into 15 frequency bands every 5Hz. Time of vibration, number of vibration and dynamic load of every frequency band are calculated. Under the dynamic load Van Mieses stress of safety pin is shown in Tale.1.

TABLE I THE LOADS SPECTRUM OF SAFETY PIN

Frequency Band （Hz）	Number of Vibration	Dynamic Load (MPa)	Percentage of Circulating γ	Cyclic Stress	Fatigue life
0～5	25109960	1.782800	0.05023	0.51645E+07	1e13
5～10	46793460	3.627585	0.09361	0.10509E+08	1e13
10～15	68128100	6.385078	0.13629	0.18497E+08	78836159590
15～20	67444292	7.739655	0.13492	0.22421E+08	15225928290
20～25	63886053	8.668516	0.12780	0.25112E+08	5778850642

25～30	54213125	8.94153	0.10845	0.25902E+08	4434717013
30～35	45778000	8.945016	0.09158	0.25913E+08	4418652629
35～40	35635046	8.989139	0.07129	0.26040E+08	4237886586
40～45	27877940	10.15652	0.05577	0.29422E+08	1492378099
45～50	20608559	7.713587	0.04123	0.22345E+08	15674276730
50～55	15511121	7.535705	0.03103	0.21830E+08	19131136480
55～60	11126646	6.638281	0.02226	0.19230E+08	56554557670
60～65	8132408	6.14563	0.01627	0.17803E+08	109314202300
65～70	5637994	5.849106	0.01128	0.16944E+08	166818722100
70～75	4009663	5.679739	0.00802	0.16453E+08	214485767900

Trough calculation of Formula 8 the total number of cycles is:

$$N = 1 / \left[\sum \frac{\gamma_i}{N_i} \right]$$

$$= 1 \Big/ \left(\frac{0.13629}{78836159590} + \frac{0.13492}{15225928290} + \frac{0.12780}{5778850642} + \frac{0.10845}{4434717013} + \frac{0.09158}{4418652629} + \frac{0.07129}{4237886586} \right.$$
$$\left. + \frac{0.05577}{1492378099} + \frac{0.04123}{15674276730} + \frac{0.03103}{19131136480} + \frac{0.02226}{56554557670} + \frac{0.01627}{109314202300} + \frac{0.01128}{166818722100} + \frac{0.00802}{214485767900} \right)$$
$$= 7300472483$$

Trough calculation of Formula 9 fatigue life of safety pin is $Y = 7300472483 / 499892367 = 14.6a$. The results meet the design requirements of safety pins.

6.Conclusions and Prospect

This paper designs safety pin which is a kind of overload protection hardware for the 5A—ZM4 transmission tower in the 《State Grid Typical Design Transmission and Distribution Projects》.The safety pin can make transmission line dissociate from tower and prevents collapse of power transmission tower and disconnection of transmission line when ice thickness exceed the numerical value that ultimate load related.

- Based on elastic-plastic theory, elastic limit load and plastic limit load of safety pin are 67KN and 114KN.In the normal conditions the load of safety pin is less then elastic limit load and safety pin meets operation requirement. The error of plastic limit load and the load of controlling tower-line separation is 0.12. After a bit load is increased safety pin fracture in the notch. Now safety pin can make transmission line dissociate from tower and then prevent tower.
- Fatigue life of safety pin which is calculated as Palmgren Miner linear fatigue damage accumulation rule is 14.6 years. So the results show that the design of safety pin can meet project requirements.

This paper introduces theoretical calculation of safety pin in detail. To achieve the purpose of reliable operation these conclusions need to be verified through finite element analysis and experiment.

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Biographies

Ju Yanzhong was born in Da An city in Ji Lin, on December 26,in 1963.He graduated from Northeastern University in January in 1988 and received a master's degree. He graduated from Beijing Jjiaotong University in April in 2004 and received a doctor's degree. Now he is the president of civil engineering Northeast Dianli University. His research direction includes in transmission project, bridges and structural seismic, structural health monitoring and diagnosis and the development and application of new materials. His major social pat-time includes members of Chinese Society for Electrical Engineering, Chinese Society of Theoretical and Applied Mechanics and Ji Lin Civil Engineering Society.