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Numerical Simulation on Structure Reliability of Electric Field Energy Harvesting Device at Tower Side under Typhoon Weather

Dongsheng Zhao*, Xiang Xiao, Xian Yang and Zhiqin Ma

Electric Power Research Institute of Guangdong Power Grid Co., Ltd., Guangzhou 510080, China

*Corresponding author e-mail: gzhaods@126.com

Abstract. As an unconventional power supply for on-line monitoring equipment, how to arrange the electric field energy harvesting device at the tower side and ensure its structural reliability in typhoon weather is worth further discussion. From the point of view of installation practicability, this paper adopts magnetic suction device, taking into account the T-shaped and circular cross-sections and modeling them. Through fluid-solid mechanical coupling simulation, the force and deformation of the device under different airflow velocities are obtained. The expression of minimum magnet suction which can ensure that the device is adsorbed stably at the side of the tower is deduced and used as the main index to measure the reliability of the structure of the device. Compared with the two kinds of device structures, the structure reliability of T-shaped collector is difficult to meet at higher wind speed, while the cylindrical collector is more reliable even when the wind speed gets high enough.

1. Introduction

High-voltage overhead transmission line is the artery of the power system. In order to ensure its safe operation, it is necessary to carry out online monitoring and timely reflect the operation status [1]. Traditional online monitoring equipment uses solar power for power supply [2] or energy collection through transformer on the power line [3-6]. However, in practical application, solar power supply is easily affected by the weather. The on-line monitoring equipment is mostly installed on the tower, so it cannot meet the practical requirements of on-line monitoring for power supply [7-9]. Therefore, how to provide reliable power supply for on-line monitoring equipment has been widely concerned.

In recent years, it has been reported that the electric field energy can be collected by cylindrical or flat-plate capacitance collector [10-14]. The author early also designed the grating electric field collector by applying flat capacitance edge effect and proposes a method by using transformer impedance transformation characteristics of AC transmission line tower side [15]. However, most of the current studies focus on the energy conversion efficiency of the electric field energy acquisition device, and there are few studies on the reliability of the device's own structure under harsh working conditions. Admittedly, how to improve the energy output of the electric field energy acquisition device is a core issue in this research. However, if the structural reliability of the device in the actual installation environment is not considered, on the one hand, the structure of the device may be affected by the external environment and change, thus reducing the energy conversion efficiency. On the other hand,



the unreliable structure may cause some security risk. Therefore, it is necessary to study the reliability of the acquisition device installed in the harsh working environment. Taking the area under the jurisdiction of China southern power grid as an example, due to its location in the coastal area, it is vulnerable to typhoons. For example, in recent years, "ute", "tiantu", "rammasun" and other strong typhoons have all posed great threats to the power grid [16]. Therefore, the structural reliability of tower side equipment installed in the region must withstand the test of typhoon weather, as does the electric field energy acquisition device.

Considering the field test and wind tunnel test is more difficult to meet the test condition and the shortcomings of high risk, so this article uses the finite element numerical simulation method which use fluid-solid mechanics coupling method to calculate the flow field around the acquisition device under different wind speed distribution and its stress and deformation of structure. Because the actual installation is planned to adopt magnetic suction structure, and under different wind speeds, in order to ensure the stable adsorption of the device on the tower side, the magnet suction required is different. So this paper takes the minimum suction required as the main measurement index of structural reliability. In addition, by adjusting the collector's appearance, this paper found that the use of streamlined collector structure can effectively improve the structural reliability of the device, but due to the weak edge effect of the structure, the efficiency of energy collecting may not be high. Therefore, how to choose the optimal layout according to the actual working environment needs to be further studied.

2. Model Description

2.1. The Geometric Model

The collector is installed at the crossarm on the side of the tower. In order to facilitate installation, the collector is fixed under the crossarm by magnetic suction structure. The magnet and the collector body are connected and locked by bolts. The geometric model of the collector is shown in Figure 1. Ten T-shaped steels with length of 1100 mm are used as the collector body, and distribute under the crossarm at equal intervals (200 mm). The section data of T-shaped steel is shown in the Figure 1. In addition, each T-shaped steel and magnet is coated with a layer of resin insulation with a thickness of 2 mm.

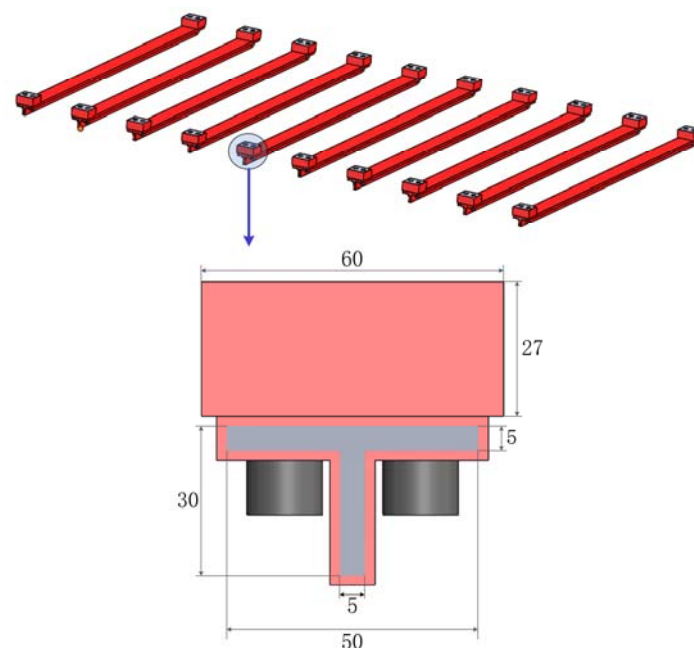


Figure 1. Geometrical model of electric field energy acquisition device for T-section steel

2.2. The Physical Model

Considering the three factors of high wind speed of the collector, high installation position (on the crossarm) of the collector and small longitudinal size of the collector itself, the corresponding inlet wind speed in the simulation can be defined as a constant wind load, and the simulation can be abstracted as fluid-solid mechanical coupling calculation. Air belongs to a fluid with a small viscosity coefficient (dynamic viscosity coefficient $\mu=17.9\times 10^{-6}$ Pa·s), which flows as a boundary layer when it sweeps over the surface of the plate. The flow velocity of the fluid passing the wall surface is almost zero at the point closest to the wall surface, and with the increase of longitudinal height, the flow velocity rises rapidly and tends to be the flow velocity of free flow. In addition, in order to use the correct equation to describe the corresponding physical process, the flow form of the fluid should be determined first, which can be generally divided into laminar flow and turbulent flow according to the size of Reynolds number:

$$Re = \frac{\rho v d}{\mu} \quad (1)$$

Where ρ is the fluid density; v is the flow rate; d is the characteristic length (generally chosen as the wall length); μ is the dynamic viscosity coefficient.

The maximum velocity $v_{\max}$ considered in this paper is 44 m/s, and the Reynolds number $Re \approx 1.6 \times 10^5$ is calculated. Computational fluid dynamics (CFD) generally takes the Reynolds number of 5×10^5 as the boundary between laminar flow and turbulent flow [17], so the laminar flow model is used in this paper. The continuity and momentum equation of this model are shown in equation 2 [18]:

$$\begin{cases} \rho \nabla \cdot (\mathbf{v}) = 0 \\ \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = \nabla \cdot [-\rho \mathbf{I} + \mu (\nabla \mathbf{v} + (\nabla \mathbf{v})^T)] + \mathbf{F} + \rho \mathbf{g} \end{cases} \quad (2)$$

Where ρ is the air density; $\mathbf{v}$ is the fluid velocity; μ is the Dynamic viscosity coefficient; $\mathbf{I}$ is the principal stress tensor; $\mathbf{F}$ is the volume force. Based on the flow field model, the structure mechanics of the collector is analyzed by considering the coupling of flow field and solid mechanics. The structural force field model equation is as follows [19]:

$$\nabla \cdot \mathbf{S} + \mathbf{F}_v = \rho^* \cdot \mathbf{a} \quad (3)$$

$$\mathbf{S} = \mathbf{S}_{ad} + \mathbf{C} : \varepsilon_{el} \quad (4)$$

Where $\mathbf{S}$ is the total stress vector; $\mathbf{F}_v$ is the load vector and is set as the fluid load on the structure; ρ^* is the density; $\mathbf{a}$ is the acceleration vector; $\mathbf{C}$ is the elastic constant matrix:

$$\mathbf{C} = \mathbf{C}(E, \nu) \quad (5)$$

Where E is young's modulus of material, set as 2×10^{11} pa (corresponding to common stainless steel material); ν is the material poisson ratio, set as 0.3. ε_{el} is the strain tensor:

$$\varepsilon_{el} = \varepsilon - (\varepsilon_0 + \varepsilon_{ext} + \varepsilon_{th} + \varepsilon_{pl} + \varepsilon_{cr} + \varepsilon_{vp}) \quad (6)$$

$$\varepsilon = \frac{1}{2} [(\nabla \mathbf{u})^T + \nabla \mathbf{u}] \quad (7)$$

Where ε is the grinn-lagrangian strain; ε_0 is the initial strain; ε_{ext} is applied externally; ε_{th} is the thermal strain under pressure; ε_{pl} is the plastic strain; ε_{cr} is the viscoelastic strain; ε_{vp} is the viscoelastic strain; $\mathbf{u}$ is the displacement field vector.

2.3. Boundary Setting and Mesh Subdivision

An air field is set around the collector, and its size is shown in Figure 2. In addition, because of the symmetry of the collector structure, 1/2 model can be adopted to simplify the calculation. The fluid inlet, outlet, and symmetrical boundaries are shown. The inlet velocity is set according to the design wind speed of Guangdong coastal line [20] (generally 35 m/s, the maximum is 44 m/s) and Beaufort level 9 and 10 (22 m/s, 25m/s). It is worth noting that the calculation process assumes that the upper surface of the magnet is fixed constraints, that is, the magnet suction is large enough. This assumption is reasonable because the suction force of the magnet can be adjusted manually according to the calculated force, so the relative displacement between the magnet and the transverse arm is not considered.

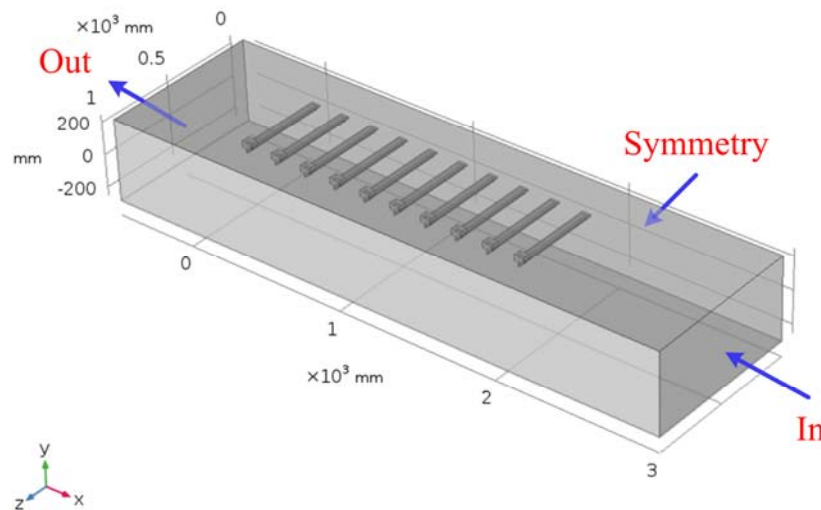


Figure 2. Boundary conditions.

Fluid calculation requires a high mesh, and the mesh division results of the model in this paper are shown in Figure 3. It can be seen from the figure that the overall grid quality is good, but near the collector, the quality of the boundary layer grid set to consider the boundary layer flow is poor. This point is often difficult to avoid in fluid calculation, because the quality criterion of triangular mesh is the maximum difference of internal angle, and the larger the difference, the lower the mass, which contradicts the form of boundary layer mesh.

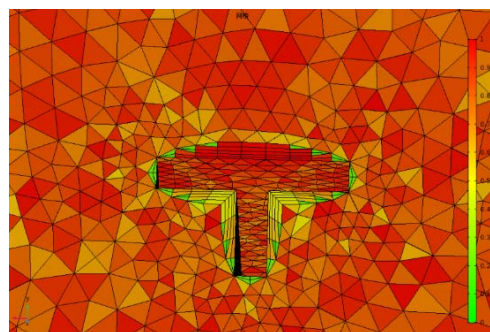


Figure 3. Mesh quality.

3. Results and Analysis

This paper is based on the finite element simulation software COMSOL Multiphysics to solve the above fluid-solid model. This section analyzes the flow field distribution around the collector, the stress and deformation of the collector, and the magnet suction reliability. In consideration of different wind loads, the calculated results are different in numerical value but similar in trend. Therefore, this paper mainly presents and analyzes the calculated results under the maximum design wind speed (44 m/s), and presents the calculated results under other wind speeds in tabular form.

3.1. The Distribution of Flow Field

Under the condition of constant wind speed of 44 m/s, the flow field around the collector is shown in figure 4. The upper surface of the collector is flat, so the airflow remains horizontal after passing. The air flow under the collector is cone shaped, which may be due to the large distortion of the vertical section of t-section steel. In order to further analyze the change of air flow field distribution from the first T section steel to the last section, the local flow field distribution diagrams of the collector's header and terminal are presented, as shown in Figure 5 (a) and 5 (b).

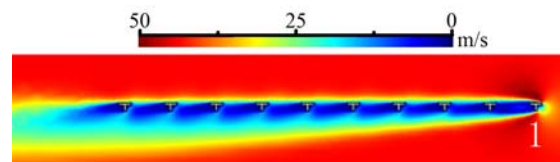


Figure 4. Global distribution of flow field.

Figure 5 uses the same legend as Figure 4, where the arrows indicate the flow direction. As can be seen from Figure 5(a), when the airflow flows through the first T-shaped steel, the wind speed will plummet and the wind direction will deflect to the upper and lower sides respectively. This trend means that the first T-shaped steel will bear a large wind load and produce a large deformation. In addition, when the air flow reaches the terminal of the collector, as shown in Figure 5 (b), the airflow velocity on both sides of the collector tends to be stable. However, by comparing 5 (a) and 5 (b), it can be found that the flow velocity on both sides of the collector decreases obviously.

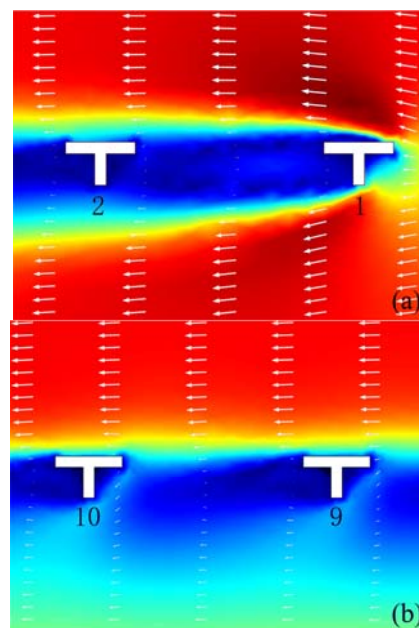


Figure 5. Local distributions of flow field around: (a) the front; (b) the end.

3.2. Stress Magnitude and Deformation

Based on the flow field distribution in section 3.1, the stress and deformation of the collector at a constant wind speed of 44 m/s are calculated, as shown in Figure 6 (a) and 6 (b) respectively. As can be seen from Figure 6 (a), the maximum stress occurs at the bolt connection between the first T-shaped steel and the magnet, and the value is about 4.2×10^6 N/mm². In addition, except for the first T-shaped steel, the stress of the collector is basically the same and the value is very small. The stress distribution is in good agreement with the calculated results. Because the first T-shaped steel is in the windward position, the airflow has a great velocity gradient on its windward surface, so it is subjected to a great wind load here. Although there is wind speed at the interval of the acquisition device, the overall stress of the acquisition device can be ignored compared with that of the first T-shaped steel due to its low peak value and small gradient. In figure 6 (b), the first T-shaped steel has the largest shape variable, which is similar to the stress distribution. The shape variables of other devices except the first one can be basically ignored. It is worth mentioning that in addition to horizontal deformation, the collector also shows vertical deformation. Figure 6 (c) and 6 (d) show both of these changes more intuitively.

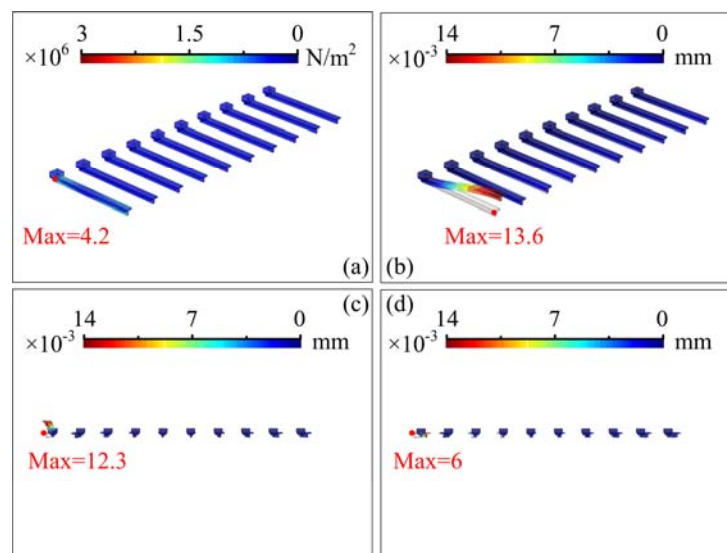


Figure 6. (a) Stress distribution; (b) Structural deformation; (c) Longitudinal deformation; (d) Horizontal deformation.

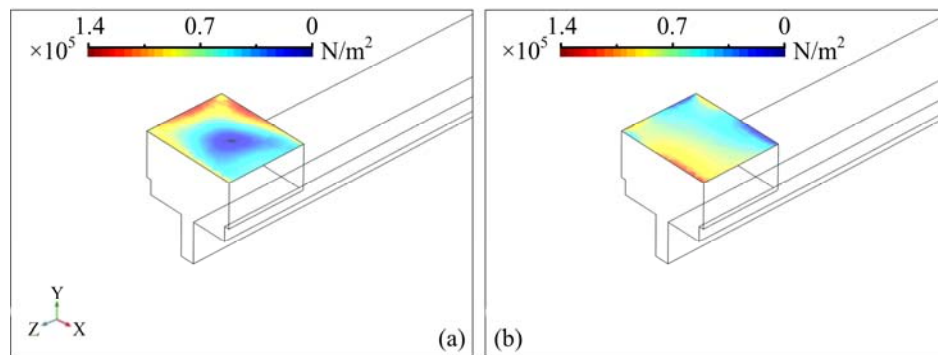
According to the results in Figure 5 and 6, the longitudinal deformation of the collector is caused by the difference between the upper and lower side pressure of the device. When the airflow flows through the first T-shaped steel, the flow velocity on the upper surface is still large, while the flow velocity on the lower (near the vertical section) drops sharply due to the large upwind surface area. The pressure in the high flow velocity area is lower than that in the low flow velocity area, and the large pressure difference leads to the longitudinal deformation. The maximum longitudinal deformation and transverse deformation were 0.0123 mm and 0.006 mm, respectively. Although the shape variable is small, because the steel itself is difficult to bend. In addition, the longitudinal deformation means that the magnet needs to provide additional normal suction to offset the counterclockwise torque in addition to the suction force greater than the steel gravity. In conclusion, it is necessary to further study the reliability of magnets under this model. The maximum stress and deformation of the collector under other constant wind speeds are shown in Table 1. The stress and shape variables increase with the increase of wind speed, but not linearly.

Table 1. Maximum stress and deformation under different wind speeds.

Items	44 m/s	35 m/s	25 m/s	22 m/s
Maximum stress (N/m ²)	4.2×10^6	4.2×10^6	4.2×10^6	4.2×10^6
Maximum deformation (mm)	0.0136	0.0086	0.0044	0.0034

3.3. Structural Reliability Assessment

As mentioned above, in order to simplify the calculation, the contact surface between the magnet and the crossarm is set as a fixed constraint, that is, there is no relative displacement between the magnet and the crossarm. The simplified feasibility condition is that the suction force of the magnet is large enough. By analyzing the flow field distribution around the collector as well as the stress and deformation of the collector itself, it is known that the working environment of the first T-shaped steel is extremely harsh. Therefore, it is very important to analyze the reliability of the first T-shaped steel. In fact, the structural reliability of the collector can be evaluated by calculating the minimum magnetic force that can ensure the device to be adsorbed stably under the crossarm. In this paper, it is considered that the greater the requirement of the magnet's suction force. The greater the wind load the structure bears, and the more unstable the structure is. In order to calculate the magnetic force, the shear stress and normal stress of the contact surface should be obtained first, as shown in Figure 7 (a) and 7 (b) respectively.

**Figure 7.** Tangential stress distribution: (a) normal stress distribution; (b) on contact surface.

As can be seen from Figure 7 (a), the shear stresses on the contact surface are all positive. This is because the direction of the fluid load on the collector points to the negative half of the z-axis. However, the calculated result is the magnitude of the stress. In order to obtain the value of the force, the stress on the contact surface should be integrated as follows:

$$F_t = \int_s St_t \cdot ds \quad (8)$$

Where St_t is the shear stress. The calculated shear force on the contact surface is 188.3 N. Since the magnet is attached below the crossarm during actual installation, the above shear force should be less than the maximum static friction force. Let the static friction factor of the contact surface between the magnet and the crossarm $\mu=0.15$. If the static friction force meets the following relation, the magnet's suction force is deemed to meet the requirements:

$$f_m = \mu f_p > F_t \quad (9)$$

Where f_m is the maximum static friction force; f_p is the pressure on the contact surface between the magnet and the transverse arm, which can be expressed by the following equation:

$$f_p = f_a - f_{eg} \quad (10)$$

Where f_a is the suction force of the magnet; f_{eg} is the equivalent gravity, which can be expressed by the following equation:

$$f_{eg} = \int_s St_n \cdot ds \quad (11)$$

Where St_n is the normal stress, as shown in Figure 8 (b). The calculated f_{eg} is approximately -22.6 N. Here the equivalent gravity is negative because the longitudinal thrust of the airflow caused by the pressure difference is greater than the gravity of the device itself. Substitute formula (8), (10) and (11) into formula (9) to get:

$$f_a > \frac{1}{\mu_s} \int_s St_t \cdot ds + \int_s St_n \cdot ds \quad (12)$$

Thus, the analytical expression of the minimum suction force required by the magnet is obtained. By substituting the relevant calculation data, it can be obtained that the magnet connecting the first t-shaped steel bar and the crossarm needs at least 1232 N of suction, while the magnet at the latter 9 T-shaped steel bars needs at least 196 N of suction on average. For other wind speeds, the suction required by the magnet is shown in Table 2.

Table 2. Minimum requirement for magnet suction (unit: N) at different wind speeds.

Items	44 m/s	35 m/s	25 m/s	22 m/s
The first steel rod	1232	779	398	308
The rest on average	196	123	63	49

It can be seen from the above table that the magnetic suction T-shaped steel acquisition device is more feasible in the case of low wind speed (such as 25, 24 m/s). However, in the case of common design wind speed (35 m/s) or maximum design wind speed (44 m/s), the first T-shaped steel has too high requirements for magnet suction, and the manufacturing cost of the magnet increases accordingly. In addition, it also indicates that the structural reliability of T-shaped steel acquisition device is difficult to meet under high wind speed, so it is not suitable to adopt this arrangement. The purpose of improving the reliability of the device and reducing the manufacturing cost is to adjust the appearance of the collector.

3.4. Structural Adjustment of Device

The original T-shaped steel collector is adjusted to a cylindrical structure, as shown in Figure 8. The number, length and spacing of the collector are consistent with the original structure. The diameter of the cylindrical section is 50 mm. It should be pointed out that only the 1/2 model is considered in the calculation process. The left contact surface is set as a fixed constraint, and the right contact surface is set as a symmetric boundary.

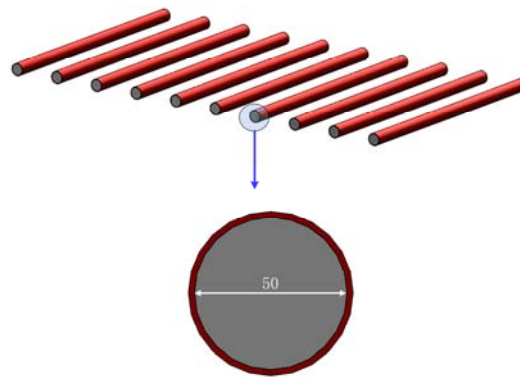


Figure 8. Geometrical model of electric field energy acquisition device for O-section steel.

Figure 9 (a) and 9 (b) respectively show the flow field distribution around the acquisition device and the local flow field distribution at the head under the wind speed of 44 m/s. As can be seen from the figure, when the airflow flows through the first cylindrical steel, the flow velocity also drops sharply and deflects to the upper and lower sides. However, compared with the T-shaped steel acquisition device, the flow field distribution on the upper and lower sides of the device is basically the same due to the good symmetry of the structure of cylindrical shaped steel. Based on the above analysis, when the upper and lower flow fields are uniformly distributed, the device will not be subjected to airflow thrust caused by the pressure difference. In other words, under the horizontal wind load, the cylindrical collector should only be deformed in the horizontal direction.

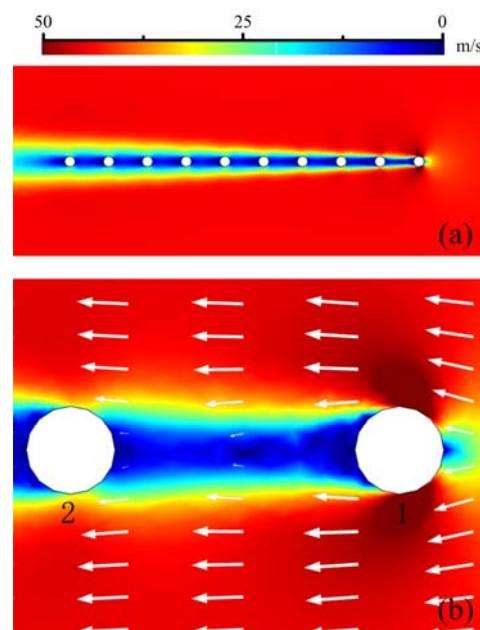


Figure 9. Global distribution of flow field: (a) local distribution of flow field around; (b) the front.

In order to study the differences between the two acquisition devices, the stress and deformation of the cylindrical acquisition device are respectively drawn in Figure 10 (a) and 10 (b). Among them, the maximum stress point and maximum deformation position are similar to the T-shaped collector, but the cylindrical collector is one order of magnitude smaller than the T-shaped collector. This is because the streamlined exterior reduces drag. The horizontal displacement and longitudinal displacement of the collector are further analyzed, as shown in Figure 10 (c) and 10 (d) respectively. The calculated

maximum horizontal displacement is 14.6×10^{-4} mm, and the maximum longitudinal displacement is 24×10^{-6} mm, with a difference of two orders of magnitude. Thus it can be seen that the symmetrical structure leads to the symmetrical flow field distribution and thus eliminates the longitudinal displacement.

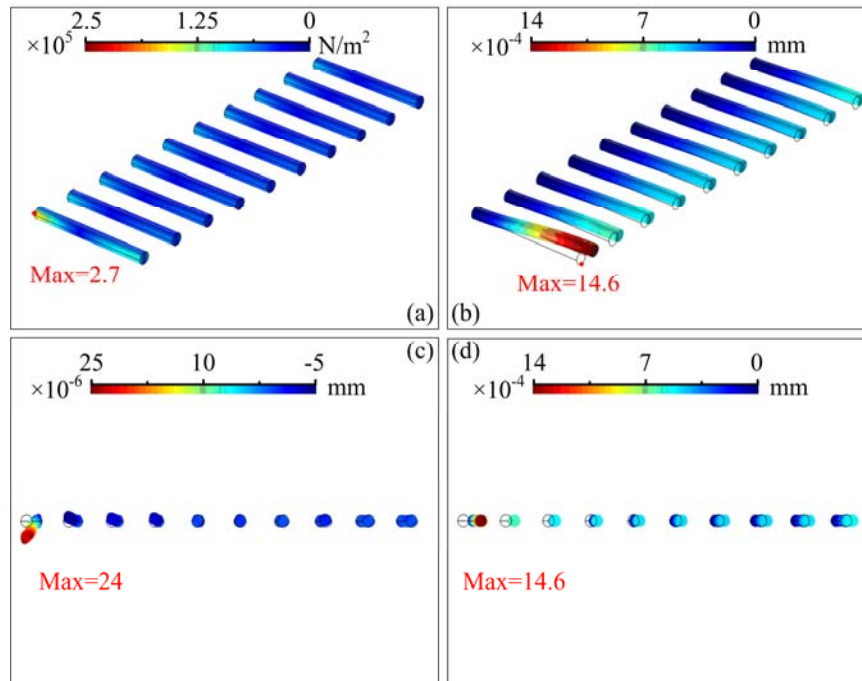


Figure 10. (a) Stress distribution; (b) Structural deformation; (c) Longitudinal deformation; (d) Horizontal deformation.

The shear force of the cylindrical collector is lower than that of the T-collector because the fluid load is smaller. Similarly, formula (8) is used to integrate the tangential stress on the fixed constraint surface, and $F_t = 42.3$ N is obtained. Since the longitudinal thrust from the airflow is very small, it can be almost ignored, so $f_{eg} = f_g = 85$ N. According to the expression of the minimum suction required by the magnet (formula (12)), the magnet needs to provide at least 367 N of suction. Compared with the data in Table 2, the magnet suction required by the cylindrical collector is greatly reduced under the same wind speed. Therefore, the structure can greatly reduce the manufacturing cost without loss of reliability.

4. Results

In this paper, modeling and finite element analysis are carried out for the structural stability of the magnetic field energy acquisition device on the tower side in typhoon weather. The calculation expression of the minimum suction force required by the magnet is derived and used as the main index to measure the structural reliability of the device. Finally, the form of the collector is adjusted and compared with the original model. The main conclusions are as follows:

1) Due to the vertical section T-shape acquisition unit and airflow direction is 90° , wind resistance is bigger, so under the same wind speed, compared with the cylindrical collector, T steel collector will be under more wind load, and generate greater deformation. In addition, the upper and lower sides of the collector with T-shaped structure will show a large difference in air pressure, resulting in longitudinal deformation. The cylindrical collector has only transverse deformation because of its symmetrical structure.

2) The magnet suction required by the T-shaped steel acquisition device at low wind speed (25 m/s, 22 m/s) is small, while the magnet suction required at high wind speed (35 m/s, 44 m/s) is significantly

increased, reaching a maximum value of 1232 N. The results show that it is difficult to satisfy the structural reliability under high wind load.

3) Under the same wind speed of 44 m/s, the magnet suction required for the first cylindrical collector is reduced to 367 N, indicating that the structural reliability of the cylindrical collector is higher than that of the T-shaped collector. Under the same reliability requirement, the cost of the cylindrical collector is relatively low.

Acknowledgments

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References

- [1] LI Chengrong, LV Yuzhen, CUI Xiang, et al. Research issues for safe operation of power grid in China under ice-snow disaster, *Power System Technology*, 2008, 32 (4): 14 - 22.
- [2] LI Yan, CHE Yong, SHAN Qiang, et al. Research on secondary system on-line monitoring and evaluation in smart substation, *Power System Protection and Control*, 2016, 44(10): 66 - 70.
- [3] FENG Jianqin, SHI Baoshan. Electronic voltage transformer based on voltage-to-current conversion, *Electric Power Automation Equipment*, 2009, 29 (4): 118 - 121.
- [4] LI Zhenyu, WU Guoliang, WANG Zhili, et al. Windage yaw disaster monitoring and early warning technology based on power micrometeorological and system implementation, *Power System Protection and Control*, 2017, 45 (1): 125 - 131.
- [5] WANG Liming, LI Haidong, CHEN Changlong, et al. A novel online energy extracting device with low lower limit deadband on transmission line, *High Voltage Engineering*, 2014, 40 (2): 344 - 352.
- [6] GONG Xianfu, ZHOU Hao, DAI Pan, et al. A design of high-power supply installed on transmission lines, *Power System Protection and Control*, 2012, 40 (3): 124 - 128.
- [7] HUANG Xinbo, ZHANG Xiaowei, LI Guochang, et al. Application of online monitoring technology of transmission lines in interconnection project from Qinghai to Tibet, *High Voltage Engineering*, 2013, 39 (5): 1081 - 1088.
- [8] CHU Shuangwei, XIONG Xiaofu, LIU Shanfeng, et al. Short-term risk assessment of power grid considering galloping prediction of transmission lines, *Power System Protection and Control*, 2018, 46 (9): 86 - 93.
- [9] HUANG Xinbo, TANG Shuxia, LIU Jiabing, et al. Design and application of on line monitoring communication network of Qinghai Tibet AC/DC interconnection project transmission line, *High Voltage Engineering*, 2013, 39 (11): 2589 - 2595.
- [10] Keutel T, Zhao X, Kanoun O. Energy scavenging for monitoring of overhead power line networks, *SENSOR+TEST Conferences*. Nürnberg, Germany: AMA Service GmbH, 2009: 207 - 212.
- [11] Zhao X M, Keutel T, Baldauf M, et al. Energy harvesting for overhead power line monitoring, *9th International Multi-Conference on Systems, Signals and Devices (SSD)*. Chemnitz, German: IEEE, 2012: 1 - 5.
- [12] Zhao X M, Keutel T, Baldauf M, et al. Power module for a wireless sensor node of a power line monitoring system, *International Multi-Conference on Systems, Signals and Devices(SSD)*. Sousse, Tunisia: IEEE, 2011: 1 - 5.
- [13] Zang H, Bretterkieber T, Brasseur G. Energy harvesting for online condition monitoring of high voltage overhead power lines, *Instrumentation and Measurement Technology Conference Proceedings*. Victoria, Canada: IEEE, 2008: 1364 - 1369.
- [14] Zang H, Bretterkieber T, Brasseur G. A feasibility study on autonomous online condition monitoring of high-voltage overhead power lines, *IEEE Transactions on Instrumentation and Measurement*, 2009, 58 (5): 1789 - 1796.
- [15] ZHAO Dongsheng, DAI Dong, LI Licheng, et al. Electric field energy harvesting around AC transmission line using impedance conversion of transformer, *High Voltage Engineering*,

- 2015, 41 (12): 3967 - 3972.
- [16] LI tianwei, JIANG siyan, ZHAO jianhua, et al. Wind disaster analysis of transmission lines in coastal areas of China southern power grid, High-voltage electrical appliances, 2016 (6): 23 – 28.
 - [17] Yang shiming, tao wenquan. Heat transfer. Edition 4, Higher education press, 2006: 206 - 209.
 - [18] YANG Shuo. Numerical simulation research on temperature field in S11-2000/10/0.4 oil-immersed transformer, Hebei: North China Electric Power University, 2016: 10.
 - [19] ZHOU Wei. VIV and vibration control of offshore pipeline considering three dimensional and whole field fluid-structure interaction, Hangzhou: Zhejiang University, 2018: 14 - 16.
 - [20] LI Tianwei, ZHAO Jianhua, CAI Yanfeng, et al. Analysis on design wind speed of transmission lines for coastal region of China Southern Power Grid, Southern Power System Technology, 2015, 9 (6): 49 - 53.