Modelling and Simulation of High Voltage Direct Current Magnetic Moment Driving Deicing Method

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Abstract. In view of the high voltage transmission line icing, the deicing method of magnetic torque driving cutters is proposed for the first time based on magnetic field of HVDC. The ampere torque in the magnetic field produce by the HVDC is used as the rotary drive, replacing the motor, providing a magnetic torque to drive the deicing mechanism. The physical model to achieve drive of magnetic torque is established by analyzing the magnetic properties around the HVDC transmission lines and the demand for magnetic torque of the robot. Magnetic torque is theoretically calculated and the relationship is analyzed between it and the model parameters. Having a comparison and analysis between the magnetic torque calculated theoretically and the simulation results after the use of software, the results turn out that the proposed method of drive system of magnetic torque in this paper is practical and it will play an significant role in the physical implementation of magnetic torque drive system for deicing robot.

1. Introduction

In most regions of China, due to the cold weather, the surface of the high voltage lines will freeze. Thus the ice on the surface of the high voltage lines will cause the fracture of the line and other problems, which will have a bad influence on social production and people’s life[1]. Deicing methods mainly includes thermal melting method, mechanical de-icing method, natural de-icing method and robot de-icing method. There are few research reports on de-icing robots both at home and abroad. In 2000, Hydro-Quebec’s Research Institute started to develop a LineROVer[3-4] teleoperated trolley as a new type of de-icing robot, which was used to remove the ice accretion on high voltage lines. After modifications and upgrades to LineROVer [5], the de-icing efficiency is improved, but the actual performance during de-icing process is not ideal. The deicing robot [6] developed by Shandong University of Science and Technology has a complex mechanical structure containing a four-bar structure. During the de-icing process, the robot is unstable, prone to tilt and has low de-icing efficiency. The motor driving ice removal robot[7] developed by Jilin University consists of an intricate structure. Its essential fundamental is that the motor drive the deicing wheel to remove the ice through the transmission of the driving system. The disadvantages of the robot such as large mass, large volume and heavy weight will increase the load of high voltage lines and cause the low working
efficiency. Beijing University of Posts and Telecommunications developed and designed a motor driving ice removal robot[8], which used two fixed pressure wheels and two driving pressure wheels to clamp the high voltage lines, and then applied rotating cutter to break and remove the ice on high voltage lines. Besides, the application of pressing wheels to clamp the high voltage lines in order to prevent slipping, will cause local bending deformation of the high voltage line. Thus the rotating cutter might cut the high voltage lines during operation.

In order to improve the matters caused by motor driving such as complex structure, high volume, heavy weight, low deicing efficiency, cutting lines, in this paper, by using the magnetic field around the high voltage direct current wire, we will arrange the reasonable layout of the electric coils and look the ampere force as the driving force to drive the deicing cutter to rotate, and then establish a physical model to fulfill the function that the magnetic moment will be treated as the power source of rotation. Besides, we’ll validate the correctness of the model by simulation which is combined with several specified model parameters. The proper deicing moment can be obtained by controlling the parameters of the model, and the cutting thickness of the cutter can be controlled by adjusting the 3-jaw chuck.

2. Principle of magnetic moment rotating driving

2.1. Analysis of magnetic field characteristics of overhead high voltage direct current transmission lines

Overhead HVDC transmission lines are generally divided into unipolar lines and bipolar lines (see figure 1). A unipolar line means using a single high-voltage transmission line to form a loop with the earth or sea water, while the bipolar line means using two high-voltage lines with different polarities.

![Figure 1. Types of overhead HVDC transmission lines](image)

Referring to Figure 1 (a), the magnetic field generated by a single high-voltage line of a monopolar line is free from external interference. Considering the mutual influence of magnetic fields generated by multiple adjacent high voltage lines, according to the right hand rule, bipolar line in Figure 1(b) will generate magnetic interference. The characteristics of magnetic field are analyzed by the bipolar circuit. The cross section of the bipolar circuit is shown in Figure 2. High-voltage lines a and b are two wires of bipolar circuits respectively, whose current sizes are almost equal while directions are opposite. Firstly, assume that the de-icing robot is carrying out ice removal actions on the high voltage line a. Secondly, take a point Q at the distance of d near the high voltage line a. Then set the magnetic induction intensity generated by the high voltage line a and b at the point Q as $B_a$ and $B_b$, and the vector sum of two magnetic field intensity is $B_{ab}$. Otherwise, the distance between both high voltage lines is $L_{ab}$ and the distance between point Q and high voltage line b is $L_{bQ}$. Besides, set the angle between the connecting line from point Q to high voltage line a and horizontal direction as $\theta$ ($0^\circ \leq \theta \leq 360^\circ$).
According to the law of cosines, we can obtain:

$$L_{abQ} = \sqrt{d^2 + L_{ab}^2 - 2d \cdot L_{ab} \cos \theta}.$$  

(1)

When $L_{ab}$ which is the distance between high voltage line a and b is taken the minimum value (i.e. point Q lies on line a or b), the magnetic field of high voltage line b is the strongest at point Q, and have the strongest influence on high voltage a. In other words, when $\theta = 0^\circ$, we can obtain:

$$\text{Min}(L_{abQ}) = L_{ab} - d.$$  

(2)

According to biot savart's law, the magnetic induction line around a single long straight wire is a concentric circle perpendicular to the plane of the wire. Then the magnetic induction intensity $B$ generated by the direct wire is deduced:

$$B = \frac{u_0 I}{2\pi r}.$$  

(3)

In the equation, vacuum permeability $u_0 = 4\pi \times 10^{-7}$ H/m. The current in dc line is $I$. The vertical distance between a point in space and the central line of a wire is $r$.

According to equation (1), (2), (3), we can obtain the magnetic intensity ratio of high voltage line a and b at the point Q respectively:

$$\frac{B_a}{B_b} = \frac{u_0 I_0}{2\pi d} \times \frac{u_0 I_0}{2\pi \times \text{Min}(L_{abQ})} = \frac{L_{ab} - d}{d}.$$  

(4)

In the equation, $I_0$ means the current size of the high voltage line.

The traditional polar distance is 22m, so wen can conduct $L_{ab}=22m$. Considering magnetic moment driving deicing robot can aviod problems such as heavy weight, so it can be assumed that the radius of driving device on the deicing robot is 0.05m. Substitute above values into the equation (4):

$$\frac{B_a}{B_b} = \frac{22 - 0.05}{0.05} = 439$$  

(5)

As we can see, $B_b$ is far less than $B_a$. Therefore, interferences caused by the magnetic field intensity of high-voltage line b at the point Q has a negligible impact on the magnetic field intensity of high-voltage line a at the point Q. So the magnetic induction line generated by high-voltage line a can be approximately the concentric circle perpendicular to the high-voltage line plane. Thus it can be
equivalent to the magnetic field generated by the monopole line in the design and analysis in the later section of this paper.

2.2. Magnetic moment driving deicing robot model and deicing device model

The solid general model of magnetic moment driving deicing robot is shown in figure 3. The deicing device is fixed on the magnetic moment drive device, which drives the deicing device to rotate. The deicing device is as shown in figure 4. The deicing device consists of a 3-jaw chuck and an ice cutter. The 3-jaw chuck can adjust the gap between the ice cutter and the high voltage line and control the ice thickness and ensure that the ice cutter will not cut the high voltage line.

2.3. Analysis of magnetic moment drive principle

Because an annular magnetic field is generated around the high-voltage direct current, a current-carrying coil should be arranged reasonably around the high voltage wire, so that the current-carrying coil is subjected to the ampere force in the magnetic field around the high voltage line. Because the annular magnetic field with certain direction will be generated around the high-voltage direct current,
the current-carrying coil should be arranged reasonably around the high-voltage wire, so that the current-carrying coil will be appropriate in height in order to make the amperage force received, and the direction of the amperage force must make the current-carrying coil rotate around the high-voltage dc wire. Using a soft magnetic materials, have assembled magnetic effect, current-carrying coil reasonable arrangement in which the current-carrying coil of ampere force is the largest, through reasonable design of the assembled magnetic core structure of strong magnetic material, in order to change the direction of the magnetic field around the high voltage direct current, to implement the current-carrying coil in under the action of ampere force, moment of ampere force current-carrying coil high-voltage dc wire rotate. The physical model of magnetic moment drive is shown in figure 5, and the magnetic core structure is shown in figure 6. The extension line of the outer wall of the convex plate, the extension line of the inner wall of the convex plate and the extension line of the center of traverse hole intersect the axis of the high voltage line. The magnetic force line in the magnetic core is shown in figure 7. The magnetic core induces the annular magnetic field around the high-voltage line into a magnetic force line that is zigzagged around the core. The force of the coil is shown in figure 8. To facilitate the modeling, the wound coil can be equivalent to multiple independent current-carrying coils. In the design model, the magnitude of the ampere generated by the magnetic field around the high voltage line of the rectangular coil embedded in the soft magnetic material and the magnitude of the rotating magnetic moment of the deicing device are calculated as follows:

Assuming that the high voltage current is \( I_0 \), the magnetic field of the wire embedded in the convex plate’s guide hole of the current-carrying coil is:

\[
B = \frac{u_r u_0 I_0}{2 \pi R}
\]  

(6)

In equation (6), \( u_r \) means the relative permeability of the magnetic core. \( u_0 \) means permeability of vacuum. \( R \) means the distance between the center of the high voltage wire and the center of the guide hole on the convex plate. Assuming the thickness of the device is \( L \) and the current in the current-carrying coil is \( I \), the magnitude of the ampere force of the wire embedded in the guide hole on the convex plate is:

\[
F_I = BIL
\]  

(7)
Take the value of the relative permeability of the magnetic core: \( u_r = 5000 \) ( \( u_0 \) means permeability of vacuum, and \( u_0 = 4\pi \times 10^{-7} \)). According to equation (6) and(7), we can conduct the ampere force of the wire embedded in the guide hole on the convex plate is:

\[
F_I = \frac{u_r u_0 I_0 IL}{2\pi R}
\]

(8)

And the magnitude of magnetic moment is:

\[
M = \frac{u_r u_0 I_0 IL}{2\pi}
\]

(9)

As the magnetic cores of the upper and lower body gathers have the inclination of gathering magnetic, the magnetic field intensity of the edge perpendicular to the guide hole in the coil is close to zero, then the ampere force on the part of the coil can be neglected. According to equation (9), the magnetic moment generated by the wire in the guide hole of the convex plate embedded in different positions is equal. Assume the number of cores is \( m \), and the number of coils is \( n \). Since every current-carrying coil has two sides to generate ampere force moment, the theoretical magnetic moment generated by the whole driving device is as follows:

\[
M_{ALL} = 2mnM = \frac{mn u_r u_0 I_0 IL}{\pi}
\]

(10)

Above content is the calculation without considering the coupling of magnetic field, so the magnetic moment of the driving device is related to the number of convex plates, the number of current-carrying coils, the current of the current-carrying coils, the HVDC current, the thickness of the driving device, the relative magnetic permeability of the magnetic core, and the vacuum magnetic permeability.

3. Model optimization

3.1. Analysis of the number of the convex plates
The magnetic drive system is composed of upper and lower body, and the convex plate is arranged symmetrically. Considering the opening and closing movement of the body, on the circle with radius equals \( R \), the central angle between the inner and outer walls of the convex plate is \( \alpha \). The central angle between the inner walls of the convex plate is \( \beta (0^\circ \leq \beta \leq 90^\circ - \alpha) \). The angular spacing of every convex plate is equal to the central angle between the inner walls of the convex plate. Then we should arrange the convex plates reasonably according to the included angle with the horizontal direction in the range of \( \beta/2 \) to \( 180^\circ - \beta \). The arrangement can refer to as figure 9. The number of the convex plates within the anglew limit is \( m_0 \), we can conduct:

\[
(2\alpha + \beta)m_0 + (m_0 - 1)\beta = 180^\circ - \beta
\]

(11)

The number of the convex plates in the whole device is \( m \):

\[
m = 2m_0 = 180^\circ / (\alpha + \beta)
\]

(12)

3.2. Analysis of the number of the coils in every convex plate in the whole model
If assuming the racial length of every convex plate is \( H \), the diameter of every guide hole is \( R_1 \), and the distance between the adjacent guide holes is \( h \). The maximum number of coils that can be placed on every convex plate is \( k_1 \):

\[
k_1 R_1 + (k_1 - 1)h = H
\]

(13)
And

\[ k_i = \frac{(H + h)}{(R_i + h)} \]

(14)

Figure 9. The arrangement of the convex plates.

Figure 10. The number of the convex plates

\( m = 4 \)

4. Simulation analysis and theoretical calculation of driving force

4.1. Establish a physical simulation model

In order to verify the correctness of the model and make the structure of magnetic moment driving system device lightweight, the parameters are instantiated based on the design and optimization of the physical model. For example, the outer wall's radius of the outer ring of the magnetic core is 50mm. The inner wall's radius of the outer ring is 47.5mm. The outer wall's radius of the inner ring is 27.5mm. The inner wall's radius of the inner ring is 25mm. And the distance between the guide hole of the most inner ring and the axis of the high voltage line is 30mm. According to the range of central angle \( \beta \) and equation (12), we can conduct the number’s range of the convex plates:

\[ 2 \leq m \leq 24 \]  

(15)

Put \( H = 22.5mm, R_i = 1.5mm \) \( h=3.5mm \) into equation (13), we can conduct: \( k_i = 5.2 \).

Thus the number’s range of the coils on every convex plate is as follow:

\[ 1 \leq n \leq 5 \]  

(16)

The soft magnetic materials used in the magnetic moment drive system are designed to use MnZn ferrite, whose relative permeability is as high as 15000. Considering the cost problem, we will take \( u_r = 5000 \). Since the current-carrying coil cannot withstand high current, we will take \( I=10A \). The radius of the high voltage wire is 20mm generally. And the current of the high voltage wire is between 1000-3000A. So we will take \( I_0=1000A \).

4.2. Simulation analysis

According to the characteristics of the model, we applied COMSOL simulation software to establish a two-dimensional model. Firstly, we set the material properties of the magnetic moment rotary driving system. And the physical field is selected as magnetic field. The surface thickness is set as
L=15mm. And external current density of the high voltage line is set as \( 1000/\frac{0.02 \times 0.02 \pi}{1000} A/m^2 \). External current density of the coil is set as \( 10/(0.0015 \times 0.0015 \times \pi) A/m^2 \). Then we could add all calculation moment’s value of the coils. Secondly, the mesh can be divided by the methods of free triangular mesh and extreme refinement. Thirdly, we should carry out the model’s solution and calculation by choosing direct solution of steady state solver.

When every convex plate has one coil, simulation work about two-dimensional models and six convex plates is processed. Through the simulation analysis, we can get the simulation sectional views as shown in figure 10 and figure 11.

As is shown in Figure 10 and Figure 11, the magnetic core induces the annular magnetic field around the high voltage line into the magnetic lines curving around the core. Magnetic coupling occurs between the magnetic field generated by the current-carrying coil and the magnetic field generated by the high-voltage line. The right hand rule is used to judge the magnetic induction direction of the high-voltage line and that of the current-carrying coil. When the former direction is identical to the latter direction, the magnetic field intensity is increased. This is the reason why the magnetic field near the inside of the guide hole is so strong. When the former direction is opposite to the latter direction, the magnetic field intensity is decreased. This is the reason why the magnetic field near the outside of the guide hole is so weak. The magnetic lines of force twist around the inner core, making them subject to the moment around the high voltage line. The simulation results are consistent with the right-hand rule theory, which proves the correctness of the magnetic moment driving principle proposed in this paper.

When there is only one coil on every convex plate, the number of convex plates is calculated by software as 2, 4, 6, 8, and 10 respectively. The size of driving magnetic moment obtained by the number of different convex plates is shown in table 1.

| m       | 2   | 4   | 6   | 8   | 10  |
|---------|-----|-----|-----|-----|-----|
| T/(N.m) | 0.58| 1.17| 1.73| 2.28| 2.76|

The magnetic moment obtained above is smaller than the theoretical magnetic moment, but very close to the theoretical magnetic moment. In the theoretical analysis, the magnetic coupling is not considered. While in the actual process, the magnetic field generated by the high voltage wire and the current-carrying coil will be coupled, making the magnetic field around the wire of the convex plate hole smaller than the theoretical magnetic field and the resulting moment smaller than the theoretical
moment. As the number of the convex plate increases, the magnetic field around the wire of the convex plate hole becomes smaller, and the actual magnetic moment is smaller than the theoretical magnetic moment.

According to the different sizes of the moments generated by different numbers of convex plates, the relation curve between the size of magnetic moments and the number of convex plates by using Matlab software to fit is shown in figure 12.

According to the characteristics of the above data, the curve type of quadratic polynomial is adopted to fit, and the polynomial can be obtained as follows:

\[ T(m) = -0.00411m^2 + 0.323m - 0.052 \]  

(17)

Firstly, we can assume that the number of convex plate is \( m = 14 \). Secondly, put the value into above equation to obtain the simulated magnetic moment \( T(14) = 3.66 \text{N} \cdot \text{m} \). Then put the value into theoretical magnetic moment equation (10), we can obtain \( M_{\text{ALL}} = 4.2 \text{N} \cdot \text{m} \). The magnetic moment differs little from the theoretical moment, which verifies the rationality of quadratic polynomial curve fitting and the correctness of magnetic moment driving principle.

When the number of convex plates of the device is 2, we will carry out simulation analysis when the number of the coils is 2 and 3 on the convex plates. Through the simulation analysis, we can get the simulation sectional views as shown in figure 13 and figure 14.

![Figure 13. The number of the convex plates n=2](image1)

![Figure 14. The number of the convex plates n=3](image2)

The right hand rule is used to determine the magnetic induction line's direction generated by the high-voltage lines and the magnetic induction line's direction generated by the current-carrying coils. When the former direction is opposite to the latter, its magnetic field strength decreases. The magnetic lines twist around the inner core, making it subject to the moment around the high-tension line. The theoretical analysis is consistent with the simulation result, which verifies the correctness of the magnetic moment driving principle proposed in this paper.

When the number of the convex plates is \( m = 2 \), we can calculate driving magnetic moments when the coil number \( n \) of every convex plates is 1, 2, 3, 4, 5 respectively. The magnitude of driving magnetic moments is obtained as shown in table 2.

| \( n \) | 1  | 2  | 3  | 4  | 5  |
|-------|----|----|----|----|----|
| \( T/ (\text{N} \cdot \text{m}) \) | 0.59 | 1.15 | 1.69 | 2.21 | 2.76 |

Table 2. The size of driving magnetic moment, \( T \), obtained by the number of different convex plates, \( m \)

According to the above table, when \( n = 1 \), the simulated magnetic moment is 0.595 \( \text{N} \cdot \text{m} \), while the theoretical moment calculated according to equation (9) is 0.6 \( \text{N} \cdot \text{m} \). The simulated magnetic moment
is very close to the theoretical moment, which verifies the correctness of magnetic moment driving principle. As the number of coils on every convex plate increases, and the current direction of guide holes on each side of the convex plate is the same, the magnetic field around guide holes of the convex plate weakens due to the coupling of magnetic field. Therefore, the simulated magnetic moment will be smaller than the theoretical moment as the number of coils on every convex plate increases.

According to the data in table 2, we can use Matlab software to fit the relation curve between the size of magnetic moment and the number of coils on every convex plates, as shown in figure 15.

In this magnetic moment driving model, when \( n \) is taken as 1, 2, 3, 4, 5 respectively, the magnitude of simulated magnetic moment differs little from that of theoretical magnetic moment, which verifies the correctness of magnetic moment driving principle.

\[
T (n) = -0.05n^2 + 0.79n - 0.19
\]  

5. Conclusions

Through the simulation analysis of the above magnetic moment driving models, the following conclusions can be obtained:

(1) The simulated magnetic moment is very close to the theoretical magnetic moment, which verifies the correctness of the driving principle of magnetic moment.

(2) In the above system device structure, the moment obtained is smaller than the theoretical value as the number of coils on each convex plate increases due to magnetic coupling. The number of convex plates and the number of coils both affect the magnitude of the moment.

(3) When the magnetic moment driving system rotates under the function of magnetic moment and the current direction of the current-carrying coil is changed, the driving moment of the system can be reversed and the steering of the driving rotation device can be controlled.

(4) The model design has good extensibility, which can be achieved not only by changing the number of coils, the size of coil current, the number of convex plates, but also the thickness of device to meet the required driving magnetic moment.
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