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# *Feasibility Study on Using Jacket Structure as Natural Grounding Electrode of Offshore Wind Turbines*

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*Abstract*— **Offshore wind power is becoming an important topic of the world's renewable energy research. Regarding the grounding of offshore wind turbines, a simulation model of the jacket structure as the grounding device is established in this paper. Every conductor of this model is divided into several segments, and the Green's function of each segment is solved with complex image method. Finally, the grounding resistance can be obtained on the basis of the principle of superposition. Moreover, this paper also analyzes several factors that affect the performance of this grounding electrode, including the depth of sea water, the resistivity of sea water and the soil resistivity of seabed. The results show that using the jacket structure as a natural grounding electrode is satisfactory for the safe grounding of offshore wind turbines.**

***Key words -offshore wind turbine; jacket structures; complex image method; grounding resistance***

## I. INTRODUCTION

With the development of wind power generation technology, offshore wind power has a wide application [1]. Offshore wind energy resources are more abundant than that on land. An offshore wind farm needs less space and has less impact due to noise compared with an onshore wind power farm [2]. Therefore, it is becoming an interesting topic of the world's renewable energy research. Regarding the grounding of an offshore wind power farm, this paper investigates the potential of using the jacket structure as the grounding medium. The investigation was carried out by building a computer-simulation model of a jacket structure which is used as the grounding device in practice. Based on the superposition principle, the Green's function is solved using the complex image method, and the grounding resistance of each wind turbine is calculated when the jacket structure is used as the natural grounding electrode for economic reason only [3-5]. This paper researched the feasibility and validity of the above grounding scheme.

## II. SOLUTION OF GROUNDING RESISTANCE BY GREEN'S FUNCTION

If a current $I$ flows into a grounding device that is buried in the ground, the potential generated by distribution currents at any point P can be obtained by means of the Green's function according to the theory of stable current field, as shown in Figure1.

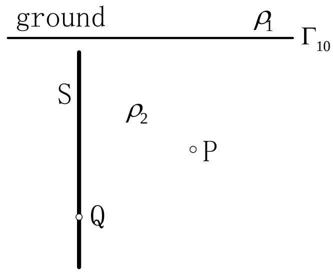


Figure 1. The Schematic diagram of Green's function of grounding electrode

Then, the potential can be evaluated as:

$$V_P = \iint_S G(P,Q)J(Q)dS \qquad (1)$$

Where $J(Q)$ is the current density at point Q which is on the surface of electrode S; $G(P.Q)$is the Green's function related to the shape of electrode.

The current flowing into the soil through the grounding grid is equal to the total current flowing in the grounding electrode.

$$I = \iint_S J(Q)dS \qquad (2)$$

Ignoring the voltage drop of the conductor, the boundary condition is:

$$V\big|_{\Gamma} = C \qquad (3)$$

Where C is a constant.

Dividing the whole grounding grid into small segments, the complex integration becomes a simple summation as in (4).

$$V_P = \sum_{j=1}^{n} G(P, O_j)\,\mathrm{I}_j \tag{4}$$

Where $G(P, O_j)$ is the potential at P caused by current source whose center is $O_j$. and $G(P, O_j)$ can show the voltage of segment *i* when the current source is in segment *j*. Defining the mutual resistance as $R_{ij}$, when i=j, $R_{ij}$ is self-resistance, then (5) can be obtained:

$$V_p = \sum_{j=1}^{n} R_{ij} I_j \tag{5}$$

Defining the potential of grounding electrode as $V_G$, and combined (5) with the boundary condition in (3):

$$\sum_{j=1}^{n} R_{ij} I_j - V_G = 0 \tag{6}$$

Finally, it can be shown that:

$$RI\text{-}AV_G=B \tag{7}$$

Where：

$$R = \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ R_{n1} & R_{n2} & \cdots & R_{nn} \\ 1 & 1 & \cdots & 1 \end{bmatrix}$$

$$A = [1, 1, \cdots, 1, 0]^T$$

$$I = [I_1, I_2, \cdots, I_n]^T$$

$$B = [0, 0, \cdots, 0, I]^T$$

According to the definition of grounding resistance, if R can be obtained, the current distribution of electrode, the ground potential rise and the grounding resistance also can be solved.

The mutual resistance ($R_{ij}$) and the self-resistance of every segment can be obtained by means of complex image method, boundary element method and so on [6-10].In this paper, the matrix R is solved for the whole grounding electrode using CDEGS software, which has been proven and used by many previous researchers.

## III. SIMULATION MODEL

The simulation model of jacket structure is shown in Figure 2

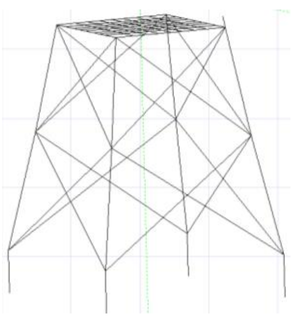

Figure 2. The geometry of jacket structure

This simulation model is equipotential. The coating of the jacket structure is ignored for calculation simplification. The size of each conductor in the jacket structure is shown in Table I and Figure 3.

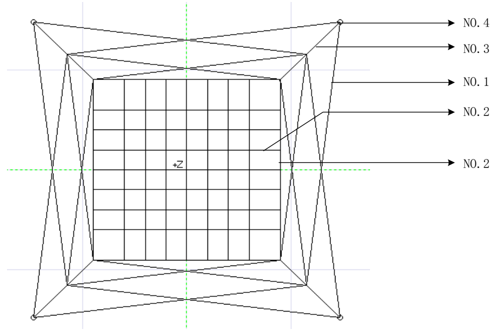


Figure 3. The top view of jacket structure

TABLE I. THE SIZE OF CONDUCTORS

| NO. | inner diameter （mm） | Outside diameter （mm） |
|---|---|---|
| 1 | 364 | 380 |
| 2 | 0 | 10 |
| 3 | 750 | 900 |
| 4 | 1050 | 1100 |

The simulation model is a two-layered horizontal soil as shown in figure 4. In the simulation model, the thickness of air is 13.84m, the depth of sea water is 5.71m, and the thickness of seabed is infinity.

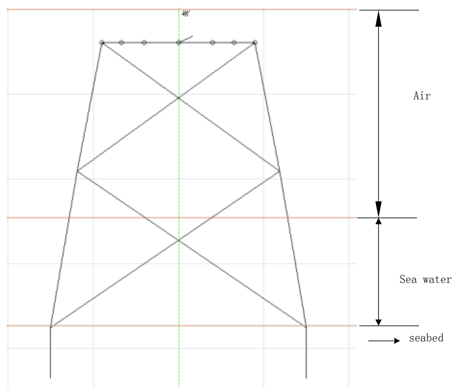


Figure 4. The schematic diagram of simulation model

Assuming the most unfavorable conditions for the resistivity of sea water to be 1Ω•m, the resistivity of seabed to be 100Ω•m, and that every conductor is divided into 10 segments, the grounding resistance is 0.121Ω, while the standard of grounding requires that the power-frequency resistance must be less than 4Ω [11], which means this grounding electrode can meet the practical requirement. It should be noted that the values of parameters used in line with accepted values [11, 12, 13].

In order to see the performance of grounding electrode under the lightning conditions, this paper uses the FFT and IFFT to calculate the resistance of the jacket structure under lightning conditions, and compares the resistance under power frequency condition with the one under lightning condition.

First, the wave of standard lightning current is converted from the time domain to the frequency domain, and then the result of the grounding impedance which is calculated under 14 different frequencies is converted to the time domain. With these steps, the voltage wave of a lightning impulse can be obtained. Then the grounding resistance can be calculated based on this voltage wave.

The equivalent of soil ionization for sea water does not exist and therefore is ignored. On this premise, the resistance is calculated using a lightning current of 10kA, a rise time for the current-wave of 2.6μs, and the corresponding fall time of 50μs and with other conditions unchanged. The result is shown in table II.

TABLE II. THE GROUNDING RESISTANCE UNDER POWER FREQUENCY CURRENT AND LIGHTNING IMPULSE

| Test current | Grounding resistance(Ω) |
|---|---|
| Power frequency | 0.121 |
| Lightning | 0.154 |

Without considering the ionization effect, the inductive effect plays a main role. According to the result, it can be seen that the grounding resistance under lightning condition is bigger than the grounding resistance under the power frequency condition, but it is still smaller than 4Ω. In general, the requirement of resistance under lightning condition is less strict than the one under power frequency current, which means the grounding electrode can meet the requirement of practical project even if it under the lightning condition.

## IV. FACTORS THAT AFFECT THE PERFORMANCE OF THE NATURAL GROUNDING ELECTRODE

The factors that affect the performance of the proposed natural grounding electrode include the depth of sea water, the resistivity of sea water and the resistivity of seabed.

### *A. The depth of sea water*

The resistivity of sea water is 1Ω•m, the resistivity of seabed is 100Ω•m, the other conditions of the simulation model are kept constant, and the depth of sea is varying.

The effect of depth of sea water on grounding resistance is shown in Table III and Figure 5.

TABLE III. RESISTANCE WITH THE DEPTH OF SEA WATER

| Depth（m） | Grounding Resistance（Ω） |
|---|---|
| 10.31 | 0.073 |
| 8.80 | 0.086 |
| 7.49 | 0.098 |
| 6.37 | 0.107 |
| 5.71 | 0.121 |

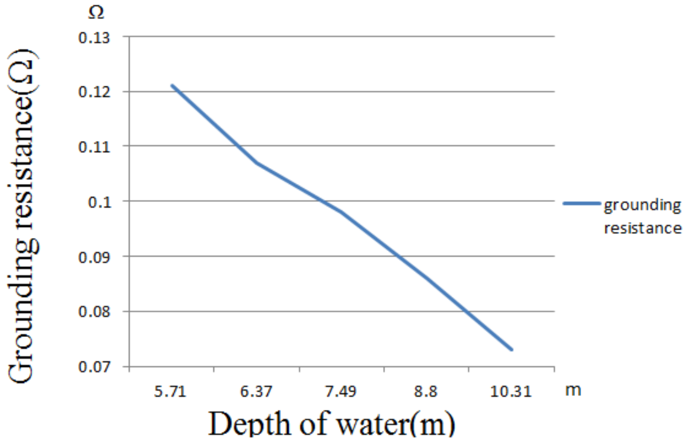


Figure 5. The correlation between the grounding resistance and the depth of water

In this simulation model, the depth of sea water varied conforms to actual condition. According to the result of simulation, the resistance becomes smaller when the water is deeper. Compared with the shallowest one and the deepest one in practice, the depth of water reduces by 44.6%, and the resistance increases by 65.7%. It can be seen that the depth of water has a great impact on grounding resistance, which means the depth of water must be considered for the evaluation of grounding electrode. When the depth of water is 0, the grounding resistance is 0.892Ω and it is smaller than 4Ω. It is obvious that the grounding electrode can meet the requirement of practical project.

### *B. The resistivity of sea water*

Keeping the resistivity of seabed at 100Ω•m, the depth of sea water at 5.71m, the resistivity of sea water was changed and the results are as shown in Table IV.

TABLE IV. THE VARIATION OF GROUNDING RESISTANCE WITH THE RESISTIVITY OF SEA WATER

| | | | | |
|---|---|---|---|---|
| The resistivity of sea water（Ω·m） | 1 | 2 | 3 | 4 |
| Grounding Resistance（Ω） | 0.120 | 0.202 | 0.267 | 0.321 |
| The resistivity of sea water（Ω·m） | 5 | 6 | 7 | 8 |
| Grounding Resistance（Ω） | 0.368 | 0.410 | 0.445 | 0.479 |

The result of simulation shows that there is a positive correlation between the resistance and the resistivity of sea water. The resistivity of sea water is usually smaller than 5Ω·m [12]. In this model, when the resistivity is 8Ω·m, the resistance is still smaller than 4Ω. This means that the resistance is not very sensitive to variations in the resistivity of sea-water.

### C. *The resistivity of seabed*

The resistivity of sea water is 1Ω•m, the level of sea is the lowest at 5.71m. The effect of resistivity of seabed on grounding resistance is shown in Table V.

TABLE V. THE VARIATION OF RESISTANCE WITH THE RESISTIVITY OF SEABED

| | | | |
|---|---|---|---|
| The resistivity of seabed（Ω·m） | 100 | 600 | 1700 |
| Grounding Resistance（Ω） | 0.114 | 0.145 | 0.154 |
| The resistivity of seabed（Ω·m） | 2700 | 3900 | blank |
| Grounding Resistance（Ω） | 0.156 | 0.157 | blank |

Because of the impact of sea water, the resistivity of seabed is much smaller than that of the soil on land. The resistivity of seabed is generally smaller than 1000Ω·m [13]. The resistance of grounding electrode increases by 27 % (from 0.114Ω to 0.145Ω) as the resistivity of seabed increases by 5 times (from 100Ω·m to 600Ω·m). When the resistivity of seabed is 3900Ω·m, the resistance is still smaller than 4Ω.

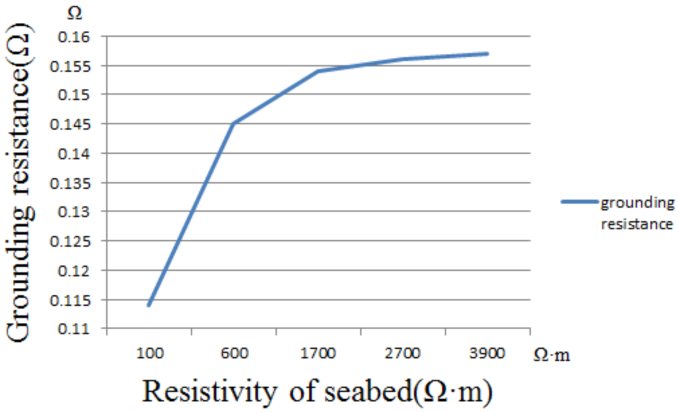


Figure 6. The correlation between the grounding resistance and the resistivity of seabed

When the resistivity of seabed is small, there is a positive correlation between it and the resistance of grounding electrode and it levels off when the resistivity of seabed reaches a large value. The correlation decreases with the increase of resistivity.

## V. CONCLUSION

With the results of the simulations, it can be seen that using the jacket structure as a natural grounding electrode for offshore wind turbine can meet the practical requirement. Although the depth of sea-water, the resistivity of sea-water and the resistivity of seabed can each affect the performance of the jacket grounding electrode, the most sensitive parameter is the depth of sea-water.

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