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Analysis and Error Separation of Capacitive Potential in the Inductosyn

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Abstract: High-precision rotor position information is usually needed in permanent-magnet synchronous motors, which are critical to high-performance motor control based on vector algorithm. Therefore, inductosyn is the best choice for the permanent-magnet synchronous motor position sensor. Capacitive potential is an important component of the ineffective potential in the inductosyn angle measuring system. When the effective potential of the inductosyn approaches zero, the proportion of capacitive potential in the output potential will be greatly amplified. As a result, the zero-position accuracy will be seriously affected. Error potential and effective potential always exist at the same time, so it is difficult to measure and study quantitatively. In this paper, the capacitance network model of inductosyn was established and the analytical calculation method was proposed. The factors affecting the capacitive potential and the suppression strategy were studied through the combination of theoretical analysis and the finite element method. In addition, the error separation method of capacitive potential was also proposed in this paper, which realized the accurate measurement of this part of error. The accuracy of the theoretical calculation and finite element analysis was verified by the experimental results.

Keywords: inductosyn; capacitive potential; error separation; suppression strategy

1. Introduction

High-precision rotor position information is the basis of high-precision vector control of the permanent-magnet synchronous motor. As the key component of the angle measurement system, the performance of the angular position sensor directly affects the working stability, conversion speed and measurement accuracy of the whole angle measurement system [1–3]. Rotary inductosyn is a multipole electromagnetic induction angular position sensor, which has the characteristics of resistance to harsh environment, low installation accuracy requirements, high accuracy, fast operation speed, strong anti-electromagnetic interference ability and low cost [4–6]. The special multipole structure enables the inductosyn to achieve a precision much higher than that of other electromagnetic measuring elements, such as rotary transformer and hall position sensor [7,8]. Compared with other optical sensors, inductosyn has stronger adaptability and reliability in extreme environments [9,10].

With the continuous development of space technology, the accuracy of an angle measurement system is of increasing necessity in various fields [11–13]. Therefore, how to improve the measurement accuracy is the main problem that inductosyn currently faces. The measurement accuracy of the inductosyn is mainly determined by the zero-position accuracy [14,15]. In addition to external factors such as installation error, conductor marking deviation, coupling potential of non-effective conductor and capacitive potential are the main factors which determine the zero-position error of inductosyn [16]. Among them, the conductor marking deviation is mainly determined by the manufacturing process, and the coupling of non-effective conductors is difficult to avoid in any structure. Therefore, the most effective method to improve the accuracy of the inductosyn system is to reduce the capacitive potential [17].
The capacitive potential is generated by the coupling capacitance between the stator and the rotor, and the current forms a loop through the coupling capacitance, generating an error potential at the output end [18,19]. The phase of the error potential and the effective potential is almost the same, which is harmful to the zero-position accuracy of the inductosyn and difficult to separate. As early as the initial stage of inductosyn research, scholars paid attention to this error factor and proposed many measures to reduce capacitive coupling [20]. These measures were based on the connection of conductors in different ways, which complicated the ends of windings and inevitably affected the electromagnetic coupling of primary and secondary windings [21].

In this study, the generation principle and influencing factors of the capacitive potential of inductosyn were analyzed. The capacitance network model of inductosyn was constructed, and the measures to suppress capacitive potential were studied by combining theoretical calculation with the finite element method. Finally, the experimental measurement was carried out by capacitive potential error separation technology, which verified the accuracy of the theoretical calculation and finite element analysis.

2. Generation Mechanism of Capacitive Potential of the Inductosyn

The rotating inductosyn is spread along the circumference, and the sine and cosine windings of the stator differ by half-pole distance in space. When the position of the sinusoidal winding and the rotor conductor completely coincide, the cosine winding is located in the center of the rotor conductor, as shown in Figure 1. When the sinusoidal excitation current is applied to the rotor winding, the two-phase windings of the stator will generate mutually orthogonal induced potentials.

\[
\begin{align*}
U_1 &= U_m \sin \omega t \\
U_{2s} &= U_0 \cos \omega t \sin \theta \\
U_{2c} &= U_0 \cos \omega t \cos \theta
\end{align*}
\]

Equation (1) shows the output effective potential of the inductosyn. However, due to the formation of a plate-like capacitor structure between the stator and rotor windings, a small part of the current flows through the distributed capacitance between the stator and rotor conductor, and generates an ineffective potential on the stator winding, as shown in Figure 1.

![Figure 1. Generation principle of capacitive potential in the inductosyn.](image)

Generally speaking, the amplitude of the effective potential in the inductosyn is much higher than that of the non-effective potential generated by the distributed capacitance. However, every time the rotor rotates an angle of the pole distance, the effective potential of stator winding will pass through the zero position, while the capacitive potential is not so sensitive to the angle change. Therefore, when the induced potential of the stator winding approaches zero, the proportion of capacitive ineffective potential in the output potential increases significantly. It can be seen that the capacitive potential will increase the zero-position error of the inductosyn, which may seriously affect the accuracy of the inductosyn angle measurement system.
3. Capacitance Network Model and Analytical Calculation of the Inductosyn

The inductosyn has the characteristic that \( X_C >> R >> X_L \). Therefore, the inductance parameter can be ignored in the analysis process, and the impedance network model of the capacitor and resistance can be directly established in the inductosyn.

3.1. Model of Stator and Rotor with Common Grounding Point

When the stator and rotor have a common grounding point, the capacitive current only passes through the air gap once to form a loop. At this time, each conductor of the rotor can be equivalent to a voltage source. The equivalent model is shown in Figure 2. The path of capacitive current is relatively simple, and it is refluxed by the grounding point of stator winding.

![Figure 2. Network model of stator and rotor with common grounding point.](image)

From the \( i \) branch on the right, the following formula can be obtained:

\[
U_i = (N - X + i)U_0 (i \leq X)
\]

\[
U_i = (i - X)U_0 (i > X)
\]

\[
R_i = iR
\]

\[
Z_1 = Z_2 = \ldots = Z_N = \frac{1}{-j\omega C}
\]

\[
E = \sum_{i=1}^{N} \frac{U_i R_i}{Z_i} = \frac{U_0 R}{Z} \sum_{i=1}^{X} (N - X + i)i + \sum_{i=X+1}^{N} (i - X)i
\]

\[
= -j\omega U_0 RN \left( \frac{X^2}{2} - \frac{N}{2}X + \frac{N^2}{4} \right)
\]

As can be seen from Equation (5), when the stator and rotor of inductosyn have a common grounding point, the generated capacitive potential grows in quadratic form, and has a large DC component. Moreover, the capacitive potential shows high order growth with the increase in the pole number.

3.2. Model of Stator and Rotor without Common Grounding Point

If one end of the stator and rotor in the inductosyn floats to the ground, the capacitive current passes through the air gap twice to form a loop. For this network, it can be divided into two impedance networks, where \( Q \) is of order \( X-1 \) and \( P \) is of order \( N-X-1 \), as shown in Figure 3.
For the unit network shown in Figure 4, the following formulas can be obtained.

\[ I_{k-1}X_c + I_k' R - I_k X_c - i_{k-1} R = 0 \]  \hspace{1cm} (6)

\[ I_k X_c + I'_{k+1} R - I_{k+1} X_c - i_k R = 0 \]  \hspace{1cm} (7)

\[ I_k = I'_k - I'_{k-1} = -(i_k - i_{k-1}) \]  \hspace{1cm} (8)

By combining Equations (6)–(8), we obtain Equation (9):

\[ I_{k+1} = (2 + 2j\lambda)I_k - I_{k-1} \]  \hspace{1cm} (9)

\[ \lambda = R\omega c \]

The result of Equation (9) is as follows:

\[ I_k = \frac{1}{\alpha^2 - \beta^2}[(I_2 - \beta I_1)\alpha^{k-1} - (I_2 - \alpha I_1)\beta^{k-1}](1 \leq k \leq X) \]  \hspace{1cm} (10)

\[ I_k = \frac{1}{\alpha^2 - \beta^2}[(I_{k+2} - \beta I_{k+1})\alpha^{k-x-1} - (I_{x+2} - \alpha I_{x+1})\beta^{k-x-1}](X + 1 \leq k \leq N) \]

\[ \alpha = 1 + j\lambda + \sqrt{2j\lambda - \lambda^2} \]

\[ \beta = 1 + j\lambda - \sqrt{2j\lambda - \lambda^2} \]

By combining Equations (8) and (10), the following equation is obtained:

\[ I'_k = \frac{1}{\alpha^2 - \beta^2}[(I_2 - \beta I_1)\alpha^{k-1} - (I_2 - \alpha I_1)\beta^{k-1}] - I_R(1 \leq k \leq X) \]  \hspace{1cm} (11)

\[ I'_k = \frac{1}{\alpha^2 - \beta^2}[(I_{k+2} - \beta I_{k+1})\alpha^{k-x} - (I_{x+2} - \alpha I_{x+1})\beta^{k-x}](X + 1 \leq k \leq N) \]

The boundary conditions of the network in area Q are as follows:

\[ I'_e = \frac{1}{\alpha^2 - \beta^2}[(I_2 - \beta I_1)\alpha^x - (I_2 - \alpha I_1)\beta^x] - I_R = 0 \]  \hspace{1cm} (12)
\[ I_1 X_c + I'_1 R - I_2 X_c - i_1 R = 0 \]  \hspace{1cm} (13)

According to the current continuity theorem, Equation (14) can be obtained:

\[ I = I_L + I_R \]  \hspace{1cm} (14)

By combining Equations (12) and (13), Equation (15) is obtained:

\[
I_1 = \frac{1}{2} I(1 - \frac{a - \beta + a^{x-1} - \beta^{x-1}}{a-x - \beta^x}) + \frac{1}{2} I_R(1 + \frac{a - \beta - (a^{x-1} - \beta^{x-1})}{a-x - \beta^x})
\]  \hspace{1cm} (15)

The boundary conditions of the network in area \( P \) are as follows:

\[
I'_N = \frac{1}{\alpha - \beta}[ (I_{x+2} - \beta I_{x+1}) \frac{1-\alpha^{N-x}}{1 - \alpha} - (I_2 - a I_1) \frac{1-\beta^{N-x}}{1 - \beta} ] = -I_R
\]  \hspace{1cm} (16)

\[ I_{x+1} X_c + I'_{x+1} R - I_{x+2} X_c - i_{x+1} R = 0 \]  \hspace{1cm} (17)

By combining Equations (14), (16) and (17), we obtain Equation (18):

\[
I_{x+1} = \frac{1}{2} I(1 - \frac{a - \beta + a^{x-1} - \beta^{x-1}}{a-x - \beta^x}) - \frac{1}{2} I_R(1 + \frac{a - \beta - (a^{x-1} - \beta^{x-1})}{a-x - \beta^x})
\]  \hspace{1cm} (18)

In the following equations, \( U_{AB} \) is solved according to the network shown in Figure 3. By the loops \( i_1, i_2, \ldots, i_L, i_{x+1}, i_{x+2}, \ldots, i_N \) and loops \( I_1, I_1', I_2, \ldots, I_{x-1}', I_x, I_L, I_{x+1}, I_{x+1}', I_{x+2}, \ldots, I_{N-1}, I_N \). It can be obtained by integrating them separately:

\[
U_{AB} = (1 + i_2 + \ldots + i_{x-1} + I_L + i_{x+1} + i_{x+2} + \ldots + i_N - 1) R
\]  \hspace{1cm} (19)

Another form of \( U_{AB} \) can be obtained from Equation (20):

\[
U_{AB} = \frac{1}{2} (i_1 + i_2 + \ldots + i_{x-1} + I_L + i_{x+1} + i_{x+2} + \ldots + i_N - 1 + I'_1 + I'_2 + \ldots + I'_{x-1} + I_L + I'_{x+1} + I'_{x+2} + \ldots + I'_N - 1) R + \frac{1}{2} (i_1 + I_L + i_{x+1} - I_N) X_c \]  \hspace{1cm} (20)

At the same time, it can be also obtained by solving \( U_{AB} \) along the loop \( I_1, I_R, I_N \):

\[
U_{AB} = (I_1 - I_N) X_C - I_R R \]  \hspace{1cm} (21)

From the above equation, we can find the expression of \( I_R \):

\[
I_R = \frac{N(a-\beta)(a+\beta-2)(a^{N-x}-\beta^{N-x})}{2(a^{N-x}-\beta^{N-x})} l
\]

\[
F = (a + \beta - 2)(N + 2)(a - \beta) - (a^{N-x-1} - \beta^{N-x-1}) - (a^{x-1} - \beta^{x-1})(a^{N-x} - \beta^{N-x})
\]

\[
+ [a - \beta + a^{N-x} - \beta^{N-x} - (a^{N-x-1} - \beta^{N-x-1})] (a^{x} - \beta^{x})
\]

\[
+ [a^{x-1} - \beta^{x-1} - (a - \beta) - (a^{x} - \beta^{x})] (a^{N-x} - \beta^{N-x})
\]  \hspace{1cm} (22)
Through Equation (22), the electric potential expression of $U_{CD}$ at the output end can be obtained:

$$U_{CD} = \sum_{j=1}^{X-1} I_j' R - I_R R + \sum_{j=X+1}^{N-1} I_j' R$$

$$= \frac{1}{\alpha - \beta} \left[ I_{X+1} \left( X - 1 - \frac{\alpha(1 - \alpha^{X-1})}{1 - \alpha} \right) - I_1 \left( X - 1 - \frac{\beta(1 - \beta^{X-1})}{1 - \beta} \right) \right] - I_R R$$

$$+ \frac{1}{\kappa - \beta} \left[ L_{X+1} \left( N - X - 1 - \frac{\alpha(1 - \alpha^{N-X-1})}{1 - \alpha} \right) - I_1 \left( N - X - 1 - \frac{\beta(1 - \beta^{N-X-1})}{1 - \beta} \right) \right]$$

(23)

The distribution law of capacitive potential of induction synchronizer under different grounding modes is shown in Figure 5. It can be seen that the relationship between capacitive potential of induction synchronizer and rotor position is sinusoidal. When there is a common ground point, the capacitive potential has a large DC component, which disappears when the rotor ends float to the ground. Therefore, in practical application, it is necessary to ensure that at least one end of the induction synchronizer is floating or that an isolation transformer is used.

![Figure 5. Capacitive potential of inductosyn.](image-url)

**4. Influencing Factors and Restraining Measures of Capacitive Potential**

The analysis above is based on some assumptions. In practical application, the capacitive potential of inductosyn is much more complex than that in the analytical model. If the capacitive potential cannot be effectively suppressed, the accuracy of the inductosyn will be greatly reduced. According to the above analysis, we have established that the capacitive potential can be effectively suppressed by isolation transformer. When the capacitive current passes through the air gap twice, the ineffective potential generated by it will be greatly reduced. In addition, we also need other methods to suppress the capacitive potential.

**4.1. Aluminum Substrate of Stator**

With the continuous development of PCB (Printed Circuit Board) technology, the cost and manufacturing cycle of inductosyn can be greatly reduced. However, organic materials are used as substrates in conventional PCB processes, and these have a certain impact on the capacitive ineffective potential. The analysis in the third section is based on the absence of any metal substrate. When the aluminum substrate is used on the stator side, the capacitance between the stator conductor and the substrate is connected in series with the capacitance between the stator and rotor, which reduces the capacitive potential on the stator conductor. The effect is related to the thickness of the stator insulation layer and the resistance of the stator substrate to the ground.

The relationship between stator substrate and capacitive potential was analyzed in this paper by the joint simulation of ANSYS Maxwell and Simplorer. The conductor structure of inductosyn is too complex; therefore, we established a simplified model with two effective conductors as shown in Figure 6, which ignored the weak coupling with other surrounding conductors, to study the influence of stator substrate on capacitive potential.
potential. Stator aluminum substrate, the distance between stator winding and substrate and the resistance of stator aluminum substrate to ground were studied as variables. In this simulation, the results are shown in Figure 7. It can be seen that using aluminum substrate can effectively reduce the capacitive potential, and the smaller the distance between the effective conductor plane of the stator and the aluminum substrate, the smaller the capacitive potential. In addition, on the basis of ensuring good insulation of stator winding, the smaller the resistance of stator substrate to ground, the lower the capacitive potential.

From the above analysis, it can be seen that the aluminum substrate structure needs to be adopted in the stator of inductosyn, and the insulation layer should be as thin as possible to effectively suppress the capacitive potential. This also verifies that the angle measurement accuracy of inductosyn made by traditional PCB process is very low. The organic substrate is too thick, so the capacitive potential is difficult to fully suppress. In order to solve these problems, we should use aluminum-based PCB processes or flexible PCB processes to produce inductosyn.

4.2. Aluminum Shielding Film

Aluminum shielding film, which covers the inductosyn conductor, is another method to suppress capacitive potential. The distributed capacitance between the stator and rotor of the inductosyn will change with the angle. However, it will become a constant value after using an aluminum shielding film. Moreover, part of the capacitive current will flow back through the shielding film when the aluminum shielding film is grounded, which will weaken the capacitive potential on the stator winding. The capacitor network model of inductosyn with shielding film is shown in Figure 8.
The capacitance between the shielding film and the exciting winding can be expressed as follows:

\[ C_{AI} = \frac{K_1 S}{D} \]  

(24)

Therefore, the impedance of capacitive current flowing back through the shielding film can be obtained:

\[ X_c = \frac{K_2 D}{j\omega S} + R_{g3} \]  

(25)

In order to make more capacitive current return from the aluminum shielding film, the impedance shown in Equation (25) should be as small as possible. Therefore, \( R_{g3} \) should be zero, which means the shielding film needs to be well grounded. Moreover, the distance \( D \) between the shielding film and the exciting winding should be as small as possible. Therefore, the aluminum shielding film should cover the side of the excitation winding.

5. Capacitive Potential Extraction and Separation Technology of the Inductosyn

5.1. Capacitive Potential Extraction

The induced potential and capacitive potential always exist at the same time, so it has been impossible to measure the size of the capacitive potential and related factors alone. Yongping Lu and others of Harbin Institute of technology estimated the capacitive potential by connecting the two ports of excitation to both ends of the stator and rotor windings, respectively, in early years [22]. However, the whole rotor is in a high potential state at this time, which is different from the distribution from 0 to power supply voltage in actual work. Therefore, the measurement results are not only larger, but also irrelevant to the relative position of stator and rotor. A special rotor that can separate the capacitive potential of the inductosyn was designed in this paper, and its principle is shown in Figure 9.

![Capacitance network model with shielding film.](image)

**Figure 8.** Capacitance network model with shielding film.

In the special rotor designed in this paper, the current mainly flows through the outer resistance, and the resistance value of each resistance is the same as that of each conductor of the inductosyn rotor. As long as the safe distance between the outer resistance and the inner conductor is ensured, the stator will not generate any induced potential. The potential on the stator side will be all capacitive potential at this time. Therefore, the capacitive non-
effective potential of the inductosyn can be separated and accurately measured through this special rotor, which is shown in Figure 10.

![Special rotor for Extracting capacitive potential.](image1)

**Figure 10.** Special rotor for Extracting capacitive potential.

### 5.2. Experimental Results of Capacitive Potential SEPARATION

The test platform of inductosyn is shown in Figure 11. In the experiment, the accuracy of the precision optical turntable is 0.5 arcsec. The capacitive potential can be measured directly with the low-noise amplification module and oscilloscope. The zero-position error of the inductosyn can be measured by rotating the fine-adjustment knob with a resolution of 0.05 arcsec of the turntable. When the angle were adjusted to make the amplified signal reach the minimum value, the difference between the displayed angle and the standard position was the zero-position error. Firstly, the capacitive potential generated by different grounding methods of stator and rotor was measured. The stator adopts a 1.6 mm thick PCB board and was fixed on the aluminum substrate. The results are shown in Figure 12. It can be seen that when the inductosyn stator and rotor have a common grounding point, a large capacitive voltage drop will be generated. Therefore, in practical application, at least one side of the stator or rotor needs to be floating to the ground, so as to significantly reduce the capacitive potential.

![Test platform of inductosyn.](image2)

**Figure 11.** Test platform of inductosyn.

In the experiment of the 360 poles of inductosyn made by PCB processes, 1.6 mm PCB stator without aluminum substrate, 1.6 mm PCB stator with aluminum substrate and 0.1 mm flexible PCB stator with aluminum substrate were selected as the experimental objects, respectively, and ensure that at least one side of the stator and rotor was floating on the ground. The relationship between stator capacitive non-effective potential and air gap
is shown in Figure 13. The experimental results are in good agreement with the simulation results. The capacitive potential decreases significantly after using the aluminum substrate. The smaller the distance between the stator conductor and the aluminum substrate, the smaller the capacitive potential, and the faster the attenuation with the increase in air gap. Therefore, the stator winding of the inductosyn should be made directly on the aluminum substrate as far as possible. If the PCB process is to be adopted, the aluminum-based PCB process or flexible PCB process fixed on the aluminum substrate are the appropriate choices.

![Figure 12. Influence of grounding mode.](image1)

![Figure 13. Influence of substrate.](image2)

In this paper, on the premise of using a flexible aluminum substrate PCB and ensuring that at least one end of stator and rotor is floating, the influence of grounding aluminum shielding film on the capacitive potential of inductosyn was measured, as shown in Figure 14. The capacitive potential of inductosyn with a shielding film was significantly reduced, and did not change with the relative position of stator and rotor.

The accuracy of the inductosyn mainly depends on the zero-position accuracy, and non-effective potential will make the zero-position error of the inductosyn jump in parity. Under the above conditions, the zero-parity errors of the inductosyn before and after the use of the shielding film were measured, as shown in Figure 15. The zero-parity error of the inductosyn before using the shielding film was very serious, and it changed greatly with the angle. After using the shielding film, the parity error decreased from about $1'$ to $10''$ and remains stable.
Influence of aluminum shielding film.

Figure 14. Influence of aluminum shielding film.

Figure 15. Parity error of inductosyn.

6. Conclusions

In this paper, the formation mechanism of capacitive potential and its harm to the accuracy of inductosyn were analyzed. Furthermore, the capacitance network model of inductosyn was established and the analytical calculation method was proposed, which reflected the distribution law of capacitive potential. This laid a foundation for the suppression of capacitive potential of inductosyn.

When the stator and rotor of inductosyn have a common grounding point, a large capacitive voltage drop is generated, which makes the inductosyn difficult to work with high accuracy. Therefore, an isolation transformer is required to ensure that one end of the stator and rotor is floating on the ground. In addition, the capacitive potential error extraction technology was also proposed in this paper. The influence of various factors on the capacitive potential was accurately measured, which provided guidance for the error separation.

Capacitive potential was effectively suppressed by stator aluminum substrate and rotor aluminum shielding film. By using both of them at the same time and ensuring the good floating of stator and rotor, we could control the capacitive potential in a very small range. The experimental results were consistent with the theoretical calculation and simulation analysis, which verified the above argument.
Author Contributions: Conceptualization, J.S. (Jianfei Sun); investigation, C.L.; Data curation, J.S. (Jianfei Sun) and Y.Z.; writing—original draft, J.S. (Jianfei Sun); writing—review and editing, C.L.; supervision, J.S. (Jing Shang). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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