Analysis and Optimization of a Radial Flux Variable Reluctance Resolver

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Abstract. Variable Reluctance resolver as a shaft position detection unit has been wildly used in harsh environments because of high reliability. This paper uses the finite element method to analyze the influence of the harmonic components in the magnetic field on the accuracy of the resolver, and proposes a method to add slots at stator combined with optimizing the output winding distributions to reduce the harmonic content in the output voltage. Finally, the sinusoidal of output voltage turned out to be improved and the resolver met the measurement accuracy of ±30°.

1. Introduction

Absolute rotor position signals provided by position sensors are needed for inverter-driven PMSM to realize communication and control algorithms [1]. Optical encoders, hall sensors and resolvers are common position sensors. The characteristic features of resolvers, such as frame-less design, shorter axial length, absolute position signal without increasing manufacturing cost, precise operation in a wide range of frequency, temperature and vibration pollution environment [2], make them suitable for automotive industry and other industrial fields. Compared with the traditional resolver, the new VR has no additional devices, such as brush and slip-ring, and only consists of a coiled stator and a salient pole rotor, which is simple in structure and convenient to process [3].

The principle is based on the salient pole effect of the rotor magnetic poles. The mutual inductance between the field winding and the output winding changes according to rotor position, and a sine and cosine voltage induced relating to the rotor rotation angle. The output voltages can be derived as follows:

\[ U_{\sin} = KU_{\text{exc}} \sin(p\theta) \]  
\[ U_{\cos} = KU_{\text{exc}} \cos(p\theta) \]

Where \( U_{\text{exc}} \) is exciting voltage, \( K \) is the resolver transformation ratio, \( p \) is the number of rotor saliences and \( \theta \) is rotational angle. Then, the angular position can be calculated from the inverse tangent of the output voltages ratio.

The ideal situation of the air gap permeance is that it only contains constant and fundamental components as the rotor position changes, so that a sinusoidal position signal is obtained in the signal winding. However, the unique structure of the resolver determines the existence of harmonic content in the air gap permeance. The harmonic content mainly comes from the difference between the actual and ideal shape of the rotor, and the slotting of the stator. In order to reduce the harmonic content in the air gap permeance, previous research has focused on analyzing and optimizing the shape of the rotor through the genetic algorithm and other methods with THD as the optimization index, while other factors that cause harmonics, such as tooth harmonics introduced by the stator, have rarely been
analyzed. The traditional optimization method involves a lot of tedious iterative calculations, which requires a lot of memory space and is very time consuming. Hence, this paper proposes a new method which is changing the stator structure combined with the optimization of the output winding distributions to reduce the harmonic content in the output voltage. This optimized method is easier to implement than just changing the shape of the rotor. Finally, the output voltage obtained by FEM and FFT analysis proved that this method can effectively improve the resolver accuracy.

2. Finite element analysis of the resolver

Main parameters of the investigated resolver are shown in Table 1 and the resolver is established as shown in figure 1. Electrical error of the resolver is ±45°, while the requirement is ±30°.

| Parameters                  | Value     | Parameters                  | Value |
|-----------------------------|-----------|-----------------------------|-------|
| Stator outer diameter       | 100 mm    | Core axial length           | 10 mm |
| Stator inner diameter       | 65 mm     | Min air-gap length          | 2 mm  |
| Turns of each exciting coil | 33        | Stator slot opening width   | 1 mm  |
| Turns of each signal coil   | 100       | Electrical error            | ±45°  |

Figure 1. Established 2D model of the initial resolver.

Figure 2. Minimum air gap length and Sine coefficient.

Ignoring a small amount of leaked magnetic flux, each pole magnetic flux enters the air gap and returns through the rotor salient poles to form a closed loop. Air gap length under each pole changes corresponding to the shape of the salient pole of the rotor, so that the air gap magnetic permeability changes in a sine wave [4]. The air gap permeance of the excitation flux corresponding to each stator tooth can be written by Fourier series as:

\[ P_i = P_0 + \sum_{\mu=1}^{\infty} P_\mu \cos \left( \mu \theta + (i-1) \frac{2 \mu \pi \rho}{Z} \right) \]  

(3)

Where \( P_0 \) and \( P_\mu \) represent the constant and \( \mu \)th harmonic components of the air-gap permeance, \( Z \) is the number of stator teeth. Two important parameters of rotor are \( K \), which is the size of the sinusoidal component in the outer shape of the rotor, and \( \delta_{\text{min}} \) are shown in figure 2. The value of \( K \) and \( \delta_{\text{min}} \) will directly affect the content of air gap permeance and each harmonic in it.

This section judges whether the values of \( K \) and \( \delta_{\text{min}} \) of the resolver are reasonable. The method is evaluating the sine of the output voltage waveform, and THD can be used as a index to judge the
distortion correspondly. The meaning of THD is described as follows:

\[
THD = \sqrt{\sum_{n=2}^{\infty} \frac{U_n^2}{U_1} \times 100\%}
\]  

(4)

Where \(U_n\) is the the effective values of each harmonic. Figure 3 shows the harmonic contents and THD distribution of different values of \(K\). The result shows that when \(K\) is 5 mm, the distortion rate is the smallest, which means \(K = 5\) is the most suitable parameter for this resolver. Different \(\delta_{\text{min}}\) can be achieved by changing the stator tooth length and rotor radial size. As shown in figure 4, \(\delta_{\text{min}} = 2\) is the best choice, which means the initial value is reasonable. However, THD is 0.918% in this structure while the qualified value is less than 0.5% based on the experience.

The best parameters can be obtained by using genetic algorithm. But it will cause a large amount of calculation owing to the complex shape of the rotor and the complex harmonic components, and the expected results may not be obtained.

### 3. Optimization of the resolver

#### 3.1. Improvement of the stator

When there are slot openings, there will exist the \(kz\)th harmonics in the air-gap permeance. Considering the influence of the \(z\)th harmonic only, the output voltage of one phase can be derived as

\[
U_{\cos} = KU_{\text{exc}} \left[ \cos(p\theta) + 1/2P_{z/p} \cos(Z - p)\theta + 1/2P_{z/p} \cos(Z + p)\theta \right]
\]  

(5)

For one two-phase resolver, \(z\) is selected as \(4p\), hence, the 3\(p\)th and 5\(p\)th harmonics are introduced into output voltages. This section proposed that adding slots at the teeth end of the stator can reduce the harmonics caused by stator slotting and increased slots with different widths at the stator teeth where magnetic density is smaller. The radial depth of the newly added slots is chosen as 1 mm according to the magnetic density distribution. The selection of the slot width should achieve the optimization requirement without affecting the magnetic circuit of the teeth. Based on the magnetic density distribution of the initial resolver stator, the new slot widths studied in this section are 1 mm as shown in figure 5, which is equal to the stator slot opening width, and 2 mm, the width of the weaker magnetic density area at teeth end. Due to the symmetrical structure of the 4-X resolver, the magnetic circuit is symmetrical, which can effectively filter even harmonics. The following figures show some major harmonic components, and some other higher orders of harmonics are neglected. The THD of the 1mm width has reduced to 0.407%, while the THD of the 2mm width has reduced to 0.408%, which proved that increasing slots at the teeth end can effectively reduce the harmonic content and improve the accuracy. The optimization results of the two widths are almost the same, with principle that the slot should be smaller, so the width of the newly added slot is selected to be 1 mm. The harmonics of optimized resolver is compared with initial model as shown in figure 6.
3.2. Improvement of winding distributions

Taking into account the sinusoidal distributed winding patterns can eliminate and suppress the higher harmonics [5], the sinusoidal distributed winding was used to further optimize the resolver in this section. However, the rounding of the turns will introduce new errors, which means that it is important to select the winding distribution properly [6]. The number of turns per tooth of the output winding is calculated and selected according to the following formula.

\[ N_s = N_s * Sin\left(\frac{2\pi P}{Z} (i-1) + \frac{\pi}{4}\right) \]  

\[ N_c = N_c * Cos\left(\frac{2\pi P}{Z} (i-1) + \frac{\pi}{4}\right) \]  

Where \( i = 1,2,...,16 \) is number of stator tooth, \( N_s \) and \( N_c \) is the winding functions, \( Z \) is the pole number of the stator, \( N \) is maximal number of the signal windings turns in the stator slot, and \( \pi/4 \) is a given adjusting angle.

The optimized distribution of turns is shown in figure 7. Combined the slots at the end of the stator teeth and the sinusoidal distributed winding, the THD reached to 0.326% and the comparison of the harmonics with initial resolver is shown in figure 8. Also, the electrical error has met the requirement of accuracy ±30’ as shown in figure 9. Figure 10 shows the magnetic flux density on the studied VR. The maximum flux density on the VR is less than 0.05 T, which means concerning about the...
saturation core of the resolver is unnecessary.

![Figure 9. The error of optimized resolver.](image1)

![Figure 10. Magnetic field of the optimized resolver.](image2)

**4. Conclusion**

This paper analyzes a resolver and optimizes it by proposing to add a slot structure at the tooth end of the stator to weaken the tooth harmonics. The results show that the increased slot width is consistent with the stator slot width. On this basis, the distribution of the output windings is changed reasonably to reduce the harmonic content together. It is demonstrated that, this method can effectively reduce the harmonic content in the output voltage and make the electrical error of the resolver less than ±30˚.

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