A study for characteristics of variable reluctance resolver considering end slot leakage inductance and eccentricity

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February 4, 2018

Abstract

Background/Objectives: As a position sensor, variable reluctance (VR) resolver is widely applied to many fields as well as electric vehicles (EV) and hybrid electric vehicles (HEV).

Methods/Statistical analysis: In this paper, a method for deriving the transformer ratio of the VR resolver is proposed by using Finite Element Method (FEM) simulations. In addition, the generalization of the inductance correction factor is studied according to the design parameter of the VR resolver such as the stack length. Moreover, the characteristics of the VR resolver when some abnormal problems occur such as eccentricity of the rotor are studied.

Findings: As a result, 2D FEM simulation is not considering the end slot leakage inductance. Therefore, 3D FEM simulation is conducted in order to derive the end slot leakage inductance. But 3D FEM simulation takes a lot of analysis time. Therefore, the correction factors of
2D FEM simulation by the VR resolver design variables such as stack length were derived. When applying the value of the correction factor using the 3D simulation, the error of transformation ratio between the experimental data and simulation data was about 3%. By applying these correction factor derivation methods, the value of the correction factor corresponding to the stack length of the VR resolver was linearly derived. In addition, when eccentricity of the rotor occurs, the output waveform of VR resolver is unbalanced due to the unbalance of the magnetic field. Therefore, the unbalance phenomenon causes a large rotor angle error. By the results of the derivation, we can judge the cause of the error when the angle error occurs due to eccentricity.

**Improvements/Applications:** VR resolver is widely applied to EV fields because it is not greatly affected by the external environment. In the future, we plan to study the characteristics of VR resolver considering leakage inductance at the same time as eccentricity occurs.

**Key Words:** Eccentricity, end slot leakage inductance, FEM, position sensor, variable reluctance resolver.

1 Introduction

Recently, the automotive industry is gradually changing from engine car that use gasoline as the main power source to HEV and EV that use motor as the main driving source due to environmental pollution and energy depletion\(^1,2\). The motor used as a driving source of EV and HEV needs to be precisely controlled under a variety of variables. Therefore, it is important to accurately know the position information of rotor in order to control the motor\(^3\). The position sensor of rotor is needed to grasp rotor information of motor. The encoder and the resolver are widely used position sensor of motor\(^4\). Compared to the encoder, resolver is not affected by the external environment such as temperature and vibration\(^5,6\). In addition, unlike the encoder, resolver can grasp the position information of rotor in the static state of motor\(^7\). Therefore, rotor position sensor of traction motor that has more vibration and disturbance is more suitable for use resolver than use encoder\(^8\).

The VR resolver has a simple structure and a structure thinner than other resolvers. Therefore, it is mainly used as a position
sensor for EV motor. The winding of the stator are wound excitement coil, COS and SIN coil. The rotor of VR resolver is a pole structure in which the reluctance changes depending on the position without a winding.

In this paper, a method for deriving the transformer ratio of the VR resolver is proposed by using the 2D and 3D FEM simulations. In addition, the generalization of the inductance correction factor is studied according to the design parameter of the VR resolver such as the stack length. Moreover, the influence of the transformation ratio when some abnormal problems such as axial-gap of the rotor. The transformer ratio of the VR resolver should be accurately derived in order to accurately grasp the position information of the rotor. Also, the transformer ratio has an influence on the back-EMF generated at the output winding. Therefore, accurately deriving the transformer ratio of the VR resolver by simulation is very important for accurate control of the motor.

2 Basic principle of VR resolver and Rotor angle derivation method

2.1 Basic principle of VR resolver

The basic principle of the VR resolver is shown in figure 1. One primary winding, called exciting winding, and secondary winding of sin and cos, called output winding, are placed in the stator instead without winding in the rotor.

If an exciting signal is applied at exciting winding, the value of reluctance is changed when the position of the rotor changes. The
secondary winding of output is placed by difference of 90 electrical degrees.

\[ E_{\sin} = K \times E_0 \times \sin \omega t \times \sin \theta \]  

\[ E_{\cos} = K \times E_0 \times \sin \omega t \times \cos \theta \]  

where \( E_0 \) is the maximum of the exciting input voltage, \( \omega (\omega = 2\pi f) \) is the frequency of exciting input voltage, \( \theta \) is the angle of rotor rotation, \( E_{\sin} \) is the induced electromotive force of sin secondary winding, \( E_{\cos} \) is the induced electromotive force of cos secondary winding, \( K \) is the transformer ratio of VR resolver. The magnetic flux passing through the air-gap during the unit time is changed by change of the reluctance when the rotor rotates. Accordingly the induced electromotive force waveform from the secondary output windings can be represented as sin, cos function by using the rotation angle as shown in equation (1) (2).

### 2.2 Rotor angle derivation method by simulation

In this paper, the rotor angle derivation of the resolver uses the arctangent method. The sampling process of the output waveforms of the sin winding and the cos winding is shown in figure 2(a). Through these sampling processes, a sinusoidal waveform can be derived as shown in figure 2(b). Using these sampled waveforms, the harmonics of the resolver are analyzed. As shown in figure 2(b), the sinusoidal waveform derived from the sampling is converted into arctangent. Consequently, the converted arctangent curve shows the angle of the rotor according to time.
Fig. 2. Processes of the rotor angle derivation (a) Extract the max value sin and cos output waveform within a cycle (b) Derive the position information by arctangent

3 Study for characteristics of VR resolver considering end slot leakage inductance

3.1 Specifications and experimental results of base model

A FEM 2D analysis model of the VR resolver is shown in figure 3(a). Model as shown in the figure is configured largely to the stator and the rotor. Input and output windings are wound at teeth in the stator. As shown in figure 3(b), x-axis and y-axis show the teeth number and turns per tooth respectively. As shown in figure, the sin winding and the cos winding are arranged with a phase difference of 90 degrees.

Fig. 3. Analysis Model of VR resolver (a) FEM 2D analysis model (b) The distribution of winding

The model applied to analysis is 16 slots and the saliency of rotor is 4X. The details of specification of the analysis model are shown in Table 1.

Table 1. The specification of analysis model
The experimental results are shown in table 2. The resistance and the impedance of the input windings are 24 Ω and 110 Ω, respectively in table 2. Transformer ratio is also known to be 0.286 (±10%).

Table 2. The experimental results of analysis model

<table>
<thead>
<tr>
<th>List</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Saliency</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Outer diameter of stator</td>
<td>89 mm</td>
<td></td>
</tr>
<tr>
<td>Inner diameter of stator</td>
<td>46 mm</td>
<td></td>
</tr>
<tr>
<td>Outer diameter of rotor</td>
<td>44 mm</td>
<td></td>
</tr>
<tr>
<td>Inner diameter of rotor</td>
<td>30 mm</td>
<td></td>
</tr>
<tr>
<td>Stack length of stator/rotor</td>
<td>4 mm</td>
<td></td>
</tr>
<tr>
<td>Ax-gap length</td>
<td>1 mm</td>
<td></td>
</tr>
<tr>
<td>Input voltage</td>
<td>3 V</td>
<td>Hz</td>
</tr>
<tr>
<td>Input frequency</td>
<td>10 kHz</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>3500 rpm</td>
<td></td>
</tr>
</tbody>
</table>

3.2 FEM analysis of base model

The transformer ratio should be firstly analyzed in order to derive the position information of the rotor. The error rate of the position information of the rotor is accurately analyzed by correctly deriving the transformer ratio.

\[
K = \frac{E_{\text{max}}}{E_0} \quad (3)
\]

\[
Z = \sqrt{R^2 + (2\pi f L)^2} \quad (4)
\]

where \(E_{\text{max}}\) is the maximum of induced electromotive force of secondary winding, \(Z\) is the impedance of input winding, \(R\) is the resistance of input winding, \(L\) is the inductance of the input winding.

In 2D FEM simulation, maximum value of the output waveform of sin winding is 3 V as shown in figure 4(a), and the effective value of the exciting input voltage is 5 Vrms. The transformer
ratio is calculated as 0.424 by equation (3). The simulation result is different from the experimental data as shown in table 2. In the FEM simulation, the value of impedance should be confirmed. Therefore, the impedance of the input winding can be obtained by using equation (4). The value of winding resistance and frequency are known by table 1 and 2. The inductance of winding can be confirmed by the results of the simulation analysis as 1.17 mH in figure 4(b). In the 2D analysis, the value of winding impedance is 77.33 Ω less than 110Ω, because the 2D analysis does not account for the end slot leakage inductance. In this case, the simulation must proceed through the 3D FEM simulation.

3D simulation is analyzed after modeling, as shown in figure 5. 3D analysis can consider end slot leakage inductance and the total inductance of the input winding is shown as 1.727mH. By comparing the inductance of the 2D and 3D analysis, the end slot leakage inductance can be calculated.

As a result, in equation (4), the impedance of the input winding is derived as 111.13 Ω which is the similar results with the measured data. The slot leakage inductance as a correction factor is applied to the input winding then the Maxwell 2D simulation was analyzed again.
The output waveform that adds a correction factor is shown in figure 6. Maximum voltage of SIN winding is 2.09 V and the transformer ratio is 2.09V / 7.071V = 0.295. The error of the transformation ratio of the actual measurement result and the simulation result is about 3%. Therefore, deriving the transformation ratio of the resolver is very important to accurately ascertain the position of the rotor.

3.3 Deduction of correction factor according to stack length

The correction factor is derived using 3D FEM simulation due to end slot leakage inductance. The transformer ratio is substantially the same as the actual experimental result when the derived correction factor is used for 2D FEM simulation. However, 3D simulation takes a lot of analysis time. Therefore, the generalization study of the correction factor is performed to reduce the analysis time according to the design variables of VR resolver. The stack length is chosen as the design variables of VR resolver. The correction factor is derived according to stack length through the method in the section above. Table III shows inductance of the 2D and 3D simulation according to stack length. The inductance increases as the stack length increases as shown in table 3.

Table 3. The inductance according to stack length

<table>
<thead>
<tr>
<th>Stack Length</th>
<th>2D Inductance</th>
<th>3D Inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm</td>
<td>1.17 mH</td>
<td>1.19 mH</td>
</tr>
<tr>
<td>6 mm</td>
<td>1.76 mH</td>
<td>2.35 mH</td>
</tr>
<tr>
<td>8 mm</td>
<td>2.35 mH</td>
<td>2.91 mH</td>
</tr>
</tbody>
</table>
The correction factor of the inductance according to stack length is shown in figure 7. It can be seen that the correction factor decreases proportionally as the stack length increases. The transformer ratio can be derived according to stack length of VR resolver through 2D FEM simulation without 3D FEM simulation from the results of figure 7.

![Fig. 7. The correction factor according to stack length](image)

### 4 Study for characteristics of VR resolver considering eccentricity

In this paper, eccentricity is defined as the nonuniform air gap that exists between the stator and rotor of VR resolver. The left figures in figure 8 show three models for comparing the characteristics of the VR resolver according to eccentricity of the rotor. In figure 8 (a) (b) (c), the base model, 0.3 mm eccentric model and 0.6 mm eccentric model are shown respectively. The right figures in figure 8 show the output waveform of three model derived using FEM analysis. As can be seen in figure 8, the VR resolver has an unbalanced waveform due to the eccentricity of the rotor. This is because the magnetic field of the VR resolver is unbalanced due to the eccentricity of the rotor. Since the reluctance changes irregularly according to the rotation angle of the rotor, the magnetic flux passing through the magnetic path also irregularly changed.
The output sampling waveform for the above three models are shown in figure 9. As shown in figure 9, the output is unbalanced when the eccentric models are compared with base model. In figure 9 (b), the angle information of the sampled waveform over time using the arctangent method are derived. It was confirmed that the error of the angle information largely occurs according to eccentricity.
Fig. 9. Comparison of angle calculation of VR resolver according to rotor eccentricity (a) Comparison of output waveform sampling (b) Comparison of angle derivation

5 Conclusion

In this paper, firstly, study on the method of deriving the transformation ratio of the VR resolver was conducted. 2D FEM simulation is not considering the end slot leakage inductance. Therefore, 3D FEM simulation is conducted in order to derive the end slot leakage inductance. But 3D FEM simulation takes a lot of analysis time. Therefore, the correction factors of 2D FEM simulation by the VR resolver design variables such as stack length were derived. As a result, when applying the value of the correction factor using the 3D simulation, the error of transformation ratio between the experimental data and simulation data was about 3 %. By applying these correction factor derivation methods, the value of the correction factor corresponding to the stack length of the VR resolver was linearly derived.

In addition, when eccentricity of the rotor occurs, the output waveform of VR resolver is unbalanced due to the unbalance of the magnetic field. Therefore, the unbalance phenomenon causes a large rotor angle error. By the results of the derivation, we can judge the cause of the error when the angle error occurs due to eccentricity.

Acknowledgment

This material is based upon work supported by the Ministry of Trade, Industry & Energy(MOTIE, Korea) under Industrial Technology Innovation Program. No.10063006, ‘Development of 2kW/kg, 100kW, IPMSM Electric Vehicle Drive System Based on High Efficiency Cooling System’.
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