3-D Finite Element Analysis of Interbar Current of V-skewed Squirrel-cage Induction Motor Taking into Account of Contact Resistance

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In this paper, we analyzed the interbar current taking into account of the contact resistance between the secondary conductor and the steel sheets of two V-skewed squirrel-cage induction motors using the 3-D parallel finite element method. We clarified the influence of the contact resistance on the interbar current in the V-skewed IM.

Keywords: 3-D parallel finite element method, interbar current, squirrel-cage induction motor, v-skew

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1. Introduction

The interbar current flows in the squirrel cage induction motor (IM) when the secondary conductor is not insulated from the steel sheets. The characteristics of the skewed IM are affected by the interbar current. We have reported the effects of rotor skew of a normal and a V-skewed IM on the interbar current under the condition that the contact resistance is assumed to be zero [1], [2].

The interbar current is affected by the contact resistance between the secondary conductor and the steel sheets. Therefore, it is important to obtain effects of the contact resistance on the interbar current. Then, we have also reported that the contact resistance of a normal skewed IM when the contact resistance was varied [3].

In this paper, we analyzed two V-skewed IMs taking into account the interbar current when the contact resistance was varied. Consequently, we clarified the influence of the contact resistance on the interbar current in the V-skewed IM.

2. Analysis Method

2.1 Magnetic Field Analysis

The fundamental equation of the magnetic field can be written using the magnetic vector potential \( \mathbf{A} \) and the electric scalar potential \( \phi \) as follows [4]:

\[
\text{rot}(\nu \text{ rot}\mathbf{A}) = \mathbf{J}_0 + \mathbf{J}_e
\]

(1)

\[
\mathbf{J}_e = -\sigma \left( \frac{\partial \mathbf{A}}{\partial t} + \text{grad} \phi \right)
\]

(2)

\[
\text{div} \mathbf{J}_e = 0
\]

(3)

where \( \nu \) is the reluctivity, \( \mathbf{J}_0 \) is the exciting current density, \( \mathbf{J}_e \) is the eddy current density, and \( \sigma \) is the conductivity.

2.2 Loss Calculation

In order to calculate the interbar current loss, we have assumed that the eddy current flows in the several steel sheets. In those steel sheets, the interbar current loss \( W \) is given as follows [4]:

\[
W = \frac{1}{T} \int_0^T \left( \int_{\Omega} \frac{(\mathbf{J}_e)^2}{\sigma} \, dV \right) \, dt
\]

(4)

where \( T \) is the period of the current waveform, \( V_e \) is the region of the steel sheet with the interbar current, and \( \sigma \) is the conductivity of the steel sheets having a vertical conductivity of zero.

The hysteresis loss and the eddy current loss occurred in the steel sheet are approximately estimated from the calculated flux density \( \mathbf{B} \) [5].

3. Analyzed Model and Conditions

In this paper, we analyzed three types IM: \( \theta \) V-skewed IM, \( \frac{\pi}{4} \theta \) V-skewed IM and normal-skewed IM.

Fig. 1 shows the analyzed model of a \( \theta \) V-skewed squirrel-cage IM. There are the contact parts between the secondary conductor and the steel sheets.

Because of the periodicity of the analyzed model, the analyzed region is 1/3 of the whole in the circumferential direction. The analyzed region is 1/1 in the axial direction in the case of the normal-skewed IM. On the other hand, because of the symmetry of the analyzed model, that is 1/2 in the axial direction in the case of the \( \theta \) V- and the \( \frac{\pi}{4} \theta \) V-skewed IM.

If all laminated steel sheets are divided by the finite element mesh with the actual thickness, the huge calculation time is required. Therefore, only 23 steel sheets are divided by the mesh with the actual thickness and some steel sheets are assumed to the steel lump which between them. The steel lump is 7 times as thick as the steel sheet and is not taking into account interbar current and eddy current. The steel sheets A, B shown in
Fig. 1(d) are the steel sheet that the analyzed interbar currents show in Fig. 4.

Figs. 2 and 3 show the secondary conductor and the definition of skew angle, respectively. In the case of the normal skewed IM and the $\theta$ V-skewed IM, the skew angle is equal to each other. On the other hand, in the case of the normal skewed IM and the $\frac{1}{2}\theta$ V-skewed IM, the contact area between the secondary conductor and the steel sheets is equal to each other.

Table 1 shows the analysis conditions. The three-phase sinusoidal wave AC of 640AT is excited to the coils. We analyzed the IM while changing the contact resistance value. The conductivity of the contact parts shown in Fig. 1(c) is calculated from the contact resistance. When the contact resistance is zero, the conductivity of contact parts is same as the steel sheets. When the contact resistance is $\infty$, the conductivity of contact parts is zero.

4. Results Calculated and Discussion

The torque is changed as the secondary current is changed due to the interbar current. Table 2 shows the average torque and the torque ripple. The average torque is calculated from the torques during the one time period taking slip into account. The torque ripple is calculated as the difference between the maximum torque and the minimum one during the one time period. Those values are normalized by the average torque ($T_{ave}$) of the normal skewed IM when the contact resistance is zero. It can be seen that the average torque is a little affected by the contact resistance regardless of skew type. It is found that the contact resistance has

![Fig. 2 Secondary conductor.](image)

![Fig. 3 Definition of skew angle.](image)

Table 1 Analysis Conditions.

<table>
<thead>
<tr>
<th>Skew-type</th>
<th>normal skewed IM</th>
<th>$\theta$ V-skewed IM</th>
<th>$\frac{1}{2}\theta$ V-skewed IM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exciting current (A)</td>
<td>640</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity (S/m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary conductor</td>
<td>3.14×10^7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel sheet</td>
<td>6.67×10^6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact Resistance</td>
<td>0, 2R, 10R, 20R, 100R, 1000R, $\infty$ (insulated)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
little effect on the torque ripple in the normal skewed IM and the \( \theta \) V-skewed IM. In the \( \frac{\pi}{2} \theta \) V-skewed IM, the torque ripple increases as the contact resistance increases, and the torque ripple of the contact resistance \( \infty \) is increased by approximately 27% compared with that when the contact resistance is zero.

Fig. 4 shows the distributions of the interbar current density vectors. Fig. 4(a) shows the steel sheet B in the normal skewed IM. Figs. 4(b) and 4(c) show the steel sheet A in the V-skewed IM. We can see that the interbar current decreases owing to the increase of the contact resistance regardless of skew type. When the contact resistance is zero, the interbar current flows in the circumferential direction between secondary conductors. On the other hand, the interbar current flows along the edge of the contact parts in the steel sheet when the contact resistance is \( 10R \), \( 100R \) and \( \infty \). It is because magnetic flux penetrating vertically through the steel sheet is generated due to skewing.

Fig. 5 shows the distributions of interbar current loss. Those values are normalized by the sum (\( \Sigma \text{loss} \)) of interbar current loss (\( \text{loss} \)), which is calculated by the normal skewed IM under the condition that the contact resistance is zero, of each steel sheet. The interbar

<table>
<thead>
<tr>
<th>Contact Resistance</th>
<th>0</th>
<th>10R</th>
<th>20R</th>
<th>100R</th>
<th>1000R</th>
<th>( \infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average torque</td>
<td>1.000</td>
<td>0.994</td>
<td>0.991</td>
<td>0.984</td>
<td>0.984</td>
<td>0.989</td>
</tr>
<tr>
<td>Torque ripple</td>
<td>0.025</td>
<td>0.026</td>
<td>0.026</td>
<td>0.024</td>
<td>0.023</td>
<td>0.024</td>
</tr>
</tbody>
</table>

**Table 2 Average torque and torque ripple**

(a) normal skewed IM

<table>
<thead>
<tr>
<th>Contact Resistance</th>
<th>0</th>
<th>10R</th>
<th>20R</th>
<th>100R</th>
<th>1000R</th>
<th>( \infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average torque</td>
<td>0.988</td>
<td>0.988</td>
<td>0.989</td>
<td>0.991</td>
<td>0.993</td>
<td>0.997</td>
</tr>
<tr>
<td>Torque ripple</td>
<td>0.023</td>
<td>0.024</td>
<td>0.024</td>
<td>0.024</td>
<td>0.023</td>
<td>0.025</td>
</tr>
</tbody>
</table>

(b) \( \theta \) V-skewed IM

<table>
<thead>
<tr>
<th>Contact Resistance</th>
<th>0</th>
<th>10R</th>
<th>20R</th>
<th>100R</th>
<th>1000R</th>
<th>( \infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average torque</td>
<td>1.059</td>
<td>1.061</td>
<td>1.062</td>
<td>1.067</td>
<td>1.069</td>
<td>1.073</td>
</tr>
<tr>
<td>Torque ripple</td>
<td>0.041</td>
<td>0.042</td>
<td>0.044</td>
<td>0.046</td>
<td>0.047</td>
<td>0.050</td>
</tr>
</tbody>
</table>

(c) \( \frac{\pi}{2} \theta \) V-skewed IM

Fig. 4 Distributions of interbar current density vectors.
current loss of each steel sheet includes the in-plane eddy current loss of the steel sheet.

In the normal skewed IM, the interbar current loss at the center of the rotor increases when the contact resistance is $10R$, and it decreases as the contact resistance increases when the contact resistance is higher than $100R$.

In the $\theta$ V- and the $\frac{\theta}{2}$ V-skewed IM, the interbar current loss decreases as the contact resistance increases.

From Figs. 5(b) and 5(c), we can see that the interbar current loss of each steel sheet increases in the V-skewed IM as the skew angle increases.

There are only a few interbar current losses in no-skewed IM [3].

Fig. 6 shows the electrical loss characteristics. Those values are normalized by the total electrical loss (Total Loss) of the normal skewed IM when the contact resistance is zero. It is found that the contact resistance has little effect on the loss except for the interbar current loss regardless of skew type.

In the normal skewed IM, the interbar current loss increases when the contact resistance is between zero and $10R$ as the contact resistance increases, and it decreases as the contact resistance increases when the contact resistance is higher than $20R$.

On the other hand, in the $\theta$ V- and the $\frac{\theta}{2}$ V-skewed IM, the interbar current loss decreases monotonically as the contact resistance increases.

Fig. 7 shows the electrical loss characteristics when the contact resistance is zero and $\infty$. Those values are normalized by the total electrical loss (Total Loss) of the normal skewed IM when the contact resistance is zero.

The total electrical loss of the normal skewed IM is larger than that of the $\theta$ V- and the $\frac{\theta}{2}$ V-skewed IM when the contact resistance is zero. On the other hand, when the contact resistance is $\infty$, the total electrical loss of the $\frac{\theta}{2}$ V-skewed IM is larger than that of the normal and the $\theta$ V-skewed IM, because the interbar current loss becomes small regardless of skew type and the secondary copper loss in the $\frac{\theta}{2}$ V-skewed IM is larger than normal and the $\theta$ V-skewed IM.

Fig. 8 shows the calculated interbar current loss characteristics. Those values are normalized by the total electrical loss (Total Loss) of the normal skewed IM when the contact resistance is zero. Regardless of skew type, the interbar current loss of the contact parts...
increases when the contact resistance is between zero and 10R as the contact resistance increases, and it decreases as the contact resistance increases when the contact resistance is higher than 20R. The interbar current loss of the steel sheets decreases as the contact resistance increases regardless of the skew type.

In order to reduce the interbar current loss, we must consider the above two interbar current losses, which changes independently with the increase of the contact resistance.

Fig. 6 Electrical loss characteristics.

Fig. 7 Electrical loss characteristics (contact resistance = 0 and ∞).

Fig. 8 Interbar current loss characteristics.
Tables 3 and 4 show the discretization data and the elapsed time, respectively.

5. Conclusion

In this paper, we analyzed two V-skewed IMs taking into account the interbar current when the contact resistance was varied. As a result, the following knowledge was obtained.

- The average torque is a little affected by the contact resistance regardless of the skew type.
- In the normal skewed IM, the interbar current loss decreases after increasing as the contact resistance increases. In the V-skewed IM, the interbar current loss decreases monotonically as the contact resistance increases regardless of the skew angle and the contact area.
- In order to reduce the interbar current loss, we must consider two factors: a decrease in the loss of the steel sheets and an increase in the loss of the contact parts.

References


Table 3 Discretization Data.

<table>
<thead>
<tr>
<th>Skew-type</th>
<th>Number of elements</th>
<th>Number of nodes</th>
<th>Number of edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal skewed IM</td>
<td>6,344,388</td>
<td>1,076,856</td>
<td>7,459,819</td>
</tr>
<tr>
<td>V-skewed IM</td>
<td>3,125,732</td>
<td>538,428</td>
<td>3,705,519</td>
</tr>
</tbody>
</table>

Table 4 Elapsed time.

(a) normal skewed IM

<table>
<thead>
<tr>
<th>Contact Resistance</th>
<th>0</th>
<th>R</th>
<th>2R</th>
<th>10R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of time steps</td>
<td>1,600</td>
<td>1,067</td>
<td>1,600</td>
<td></td>
</tr>
<tr>
<td>Elapsed time (hours)</td>
<td>555.3$^*$</td>
<td>344.0$^*$</td>
<td>348.4$^*$</td>
<td>606.3$^*$</td>
</tr>
</tbody>
</table>

(b) V-skewed IM

<table>
<thead>
<tr>
<th>Contact Resistance</th>
<th>0</th>
<th>R</th>
<th>2R</th>
<th>10R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of time steps</td>
<td>1,067</td>
<td>1,600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elapsed time (hours)</td>
<td>385.3$^*$</td>
<td>740.0$^*$</td>
<td>1,011.3$^*$</td>
<td>1,356.4$^*$</td>
</tr>
</tbody>
</table>

(c) $\frac{1}{2}\theta$ V-skewed IM

<table>
<thead>
<tr>
<th>Contact Resistance</th>
<th>0</th>
<th>R</th>
<th>2R</th>
<th>10R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of time steps</td>
<td>1,067</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elapsed time (hours)</td>
<td>192.1$^*$</td>
<td>300.4$^*$</td>
<td>310.2$^*$</td>
<td>433.3$^*$</td>
</tr>
</tbody>
</table>

Elapse time (hours) and Computer used: *1 Intel Xeon (3.4GHz) ×16
*2 Intel Xeon (3.5GHz) ×16
*3 Intel Corei7 (3.4GHz) ×16