Analysis and Loss Reduction of a Canned Switched Reluctance Drive from the Windings Perspective

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Abstract- The can loss is the biggest constraint for canned drives at high speed. In this paper, the can loss of a canned switched reluctance machine (SRM) is analyzed. Then, the can loss is reduced by investigating topology of windings based on the spatial winding distribution theory. A new mathematical model is built up by considering arrangement of wires within a coil. The proposed winding topology is verified by simulation that not only can loss but iron loss can be suppressed at any speed and meanwhile the active torque is enhanced.

Keywords- switched reluctance machine; canned machine; can loss reduction; windings design

I. INTRODUCTION

The canned motor is often used in sealed environment such as pumps and nuclear power, and is the key component responsible for power and motion [1]. Such kind of motor is distinguished by having a can in the air gap as partition to prevent each part of the machine from erosion by outer liquid.

For pump drives, the classic solution is the use of caged induction machines. But recently, switched reluctance machines are developed as a competitive alternative [2].

The SRM is of simple structure, low cost and robustness, and able to brake frequently. As to canned SRMs, two cans should be equipped respectively on the stator (stator can) to isolate windings and on the rotor (rotor can) to reduce friction caused by cavity [3].

The can material is metal and the resistivity is preferred as large as possible to resist eddy current on the cans [4]. The thickness is required as thin as possible to make shorter air gap. Unlike the machine body, the can shield is not difficult to be laminated and large eddy current on both cans, called can loss, occurs especially at high speed. The machine can’t be applied without loss reduction.

II. THE CAN LOSS ANALYSIS

Initially based on an ordinary SRM, the machine is designed by simply adding two cans in the air gap. The geometry of a 3-phase 12/8 type is shown in Fig.1. Between cans there is cooling liquid to remove heat from can loss.

Traditional concentrated windings are used. Such topology is characterized by all turns wound onto a single tooth. The number of turns per pole $N_{TP}$ and maximum phase current $I_{ph}$ should coordinate to achieve required MMF (Magneto Motive Force) once the required torque is given.

![Fig.1. Overview of the canned SRM](image1)

The can loss (sum of both cans) is shown in Fig.2. The curve is characterized by two peaks at the rotor position where the phase current rises up or drops down.

![Fig.2. The can loss waveform at the speed of 6000rpm](image2)

It is also shown in Fig.2 that the two peaks together means almost total loss. The highest peak occurs when phase current is on the way of dropping. Starting from the turn-off angle, the real-time air gap reluctance is very small because teeth are almost aligned and the rate of change of flux in the air gap is subjected to severe alternation.
III. THE WINDING MODELS

The losses include can loss, iron loss and copper loss. The copper loss is the product of phase current and resistance of windings, and the resistance depends on material, geometry of wires and temperature when the machine is running. Moreover at high speed, loss is considerable and especially the can loss becomes the principal heat source.

The can loss reduction is highly required and meanwhile the active torque should be maintained as much as possible. In this paper the reduction method is investigated from windings point of view.

The non-overlapping tooth concentrated windings are the compact design with low cost and copper loss. However, the MMF distribution is not a sinusoidal waveform and contains more space harmonics. More vibration and loss occur consequently.

In the following, the MMF model is created using Fourier method. Considering phase current, such a model starts from topology of a single coil, then spatial distribution of all coils. Two different models of a coil are described below.

A. Model of a coil (Model 1)

Usually, a coil is considered as integrity. Fig.3(a) shows a model of one coil in a stator slot. The conductor is transferrable to the surface with opening width \( w_{\text{St}} \) while the slot itself is filled with iron, as the iron permeability is very large against that of air Fig.3(b).

As to the machine, in one slot there are two parts from different coils (Fig.4), and each is transferred to surface with half of the slot width. The distance between two sides of a coil is tagged with \( w_{\text{Co}} \), a parameter related with width of teeth.

The phase current is a prerequisite for MMF modeling. In SRMs, the waveform follows a trapezoid characterized by upper limit and the rate of rising up and dropping down. When the turn-on and turn-off angles are reached, the phase current is approximately considered rising up or dropping down linearly with rotor position.

The MMF \( \Theta \) generated by one coil is modeled (Fig.5). The rectangular blocks represent half of a coil with signs of current flow. The trapezoidal waveform is expressed by the width of half of the coil \( w_{\text{St}}/2 \) and distance \( w_{\text{Co}} \). With number of pole pairs \( p = 2 \), the expression \((\pi / \tau_p)\) converts all measurements into electrical angle \( \beta \), where \( \tau_p \) refers to pole pitch and \( \beta \) represents circumferential direction.

\[
\Theta(\beta) = \sum_{v=1,2,3...}^{2i} \frac{\pi}{v^2} v \xi_N \xi_S \cos \left( \frac{v}{p} \beta \right) \quad v / p = 1,2,3...
\]

\[
v \xi_N = \sin \left( \frac{v}{p} \frac{w_{\text{St}} \pi}{2 \tau_p} \right) \quad \tau_p = \frac{w_{\text{Co}} \pi}{2 \tau_p} \quad v \xi_S = \sin \left( \frac{v}{p} \frac{w_{\text{Co}} \pi}{2 \tau_p} \right)
\]

where \( v \) is the circumferential harmonic number.

\( v \xi_N \) is slot opening factor characterized by width of stator slot while \( v \xi_S \) is short pitch factor by the ratio of coil pitch to pole pitch. They are altogether called winding factor.

B. Model of a coil (Model 2)

This model is characterized by how different turns within a coil are wound onto the tooth. The winding topology is shown in Fig.6. Each ring stands for a single turn with diameter \( d_{\text{Wir}} \) and current direction. There is arbitrary number of turns per pole \( N_{T_p} \), and on each tooth there are \( S \) layers of wires. A layer refers to a group of turns from vertical direction, and so in one layer there are \( N_{T_p} / S \) turns.
However, different layers have different widths. Originally (Fig. 7a), to make the width identical, all layers have to be regrouped. The matching principle is shown in Fig. 7b. Such modification is feasible as identical MMF can be generated. However, the symmetry axes of layers after regrouping are not always overlapping onto the central axis of the tooth. Consequently, there are potential differences when summing up all layers based on the first layer.

In analogy to Fig. 5, the MMF waveform by the proposed coil is investigated. Such target starts from a single turn. The MMF waveform by any turn \( \chi \) is shown in Fig. 8.

In analogy to Fig. 5, half of the width of stator slot \( w_{slt}/2 \) is replaced by diameter of wires \( d_{wir} \). The width between two sides of a turn is re-expressed as \( (w_{co}+2d_{wir}) \). Like pole pitch \( \tau_p \), \( \tau_{p,\chi} \) refers to a quarter of circumference measured from center of the machine to the \( \chi \)-th wire. The slot opening factor and short pitch factor are respectively written as (The subscript \( \chi \) indicates that such factor relates to a single turn and the name of the factors are only nominal),

\[
\begin{align*}
\varepsilon_{N,X}^{\chi} &= \sin \left( \frac{v}{p} \frac{d_{wir} \pi}{\tau_{p,\chi}} \right) \\
\varepsilon_{S,X}^{\chi} &= \sin \left( \frac{v}{p} \frac{w_{co} + S d_{wir} \pi}{\tau_{p,\chi}} \right)
\end{align*}
\]

Next, all turns in one layer of a coil are summed up. The average phase difference \( \beta_{L,1} \) from all \( N_{TP}/S \) turns in a layer is used for simplicity. The MMF of the first layer of turns is written as

\[
\Theta(\beta) = \frac{N_{TP}}{S} \sum_{\chi=1}^{N_{TP}/S} \varepsilon_{N,X}^{\chi} \varepsilon_{S,X}^{\chi} \cos \left( \frac{v}{p} (\beta - \beta_{L,1}) \right)
\]

Finally, all layers in a coil are summed up. As has been said, there is a potential difference for each layer. The move in length by \( \gamma \)-th layer from Layer 1 is expressed as \(- (\gamma-1)d_{wir}\). Minus sign indicates clockwise. Similarly, another \( (\pi / \tau_{p,\gamma}) \) is affiliated to convert the move into electrical angles. In analogy, \( \tau_{p,\gamma} \) means quarter of the circumference measured from center of the machine to middle of any layer \( \gamma \), and is expressed as

\[
\tau_{p,\gamma} = \tau_p + \pi \frac{N_{TP}}{4S} d_{wir}
\]

Sum of all layers in a coil is modeled and solved by the following expression

\[
\sum_{\gamma=1}^{N_{TP}/S} e^{j(\beta \gamma / \tau_{p,\gamma})} = \frac{\sin \left( \frac{\lambda}{2} \right)}{\sin \left( \frac{\lambda}{2} \right)}
\]

Using sum of unit vectors as the equation shown below,

\[
\sum_{\gamma=1}^{N_{TP}/S} e^{j(\beta \gamma / \tau_{p,\gamma})} = \sum_{\gamma=1}^{N_{TP}/S} e^{j(\lambda \beta / \tau_{p,\gamma})}
\]

The distribution factor \( \xi_{\chi} \) describes the MMF influenced by geometry and distribution of wires. It takes a layer as unit and is expressed as
distribution by Model 1 and 2 are respectively written
as $N_{phi}$ where $4\pi$ vertical upright.

The parameters in the winding function theory, it is achieved by sum of all coils.

Next, the MMF distribution is investigated. Starting from the coil. Additionally, another part $\pi (p-1)$ is used to account for current reversal.

The mechanical angle between teeth is $2\pi / 4N_{ph} = \pi / 2N_{ph}$, where $4N_{ph}$ is the number of stator teeth. So the angular expression of $k$-th phase is $(k-1) \pi r / N_{ph}$.

By sum of all coils and then sort of harmonics, the MMF distribution of all coils $S$ is shown in Tab.1 that the iron loss and can loss are hardly investigated.

The winding factor is closely related with diameter of wires $d_{Wir}$ and number of layers $S$. In the following, each parameter is investigated.

The wire diameter is responsible for winding resistance. It is shown in Tab.1 that the iron loss and can loss are hardly changed, but copper loss is reduced by a larger diameter.

<table>
<thead>
<tr>
<th>Wire diameter (mm)</th>
<th>Iron loss (W)</th>
<th>Can loss (W)</th>
<th>Copper loss (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>456</td>
<td>4338</td>
<td>1164</td>
</tr>
<tr>
<td>2.7</td>
<td>454</td>
<td>4316</td>
<td>1459</td>
</tr>
<tr>
<td>2.3</td>
<td>452</td>
<td>4297</td>
<td>1945</td>
</tr>
</tbody>
</table>

The number of layers in a coil is expressed by distribution factor. Fig.11 shows the value of $\chi_{\phi r}$ as a function of harmonics order. For $S=1$ (single layer of wire), the amplitude of any harmonic remains the same. With layers increasing, the higher
orders are suppressed. Thus coils of large width help to resist harmonics of higher orders.

![Fig.11. Distribution factor under number of layers](image1)

![Fig.12. The MMF harmonics by number of layers](image2)

The MMF harmonics are shown in Fig.12. The first and third are working harmonics while the rests are responsible for vibration and losses. With higher number of layers ($S=5$, e.g.), the amplitude of working harmonics are enhanced while others are suppressed, which means the active torque is higher with lower loss at the same time.

![Fig.13. The new winding topology (left: conventional, right: improved)](image3)

In practice, the wire diameter and layers are confined by slot geometry. Usually windings are of 2 layers and each with 5 turns. Meanwhile, a large diameter of wires is expected. With layers increased, coils from adjacent phases may collide or mutually inducted strongly. To reduce losses, an overlapping structure with more layers is proposed (Fig.13, right).

![Fig.14. The improved torque and reduced loss waveforms](image4)

The torque and loss curves by different winding topologies are shown in Fig.14. Both active torque and loss are improved at the same time under different speed. The iron loss is also reduced (Tab.2). All are calculated from FEM.

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Iron loss (W)</th>
<th>Iron loss (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>original windings</td>
<td>improved windings</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>98</td>
<td>90</td>
</tr>
<tr>
<td>3000</td>
<td>205</td>
<td>181</td>
</tr>
<tr>
<td>6000</td>
<td>452</td>
<td>404</td>
</tr>
</tbody>
</table>

V. CONCLUSION

The loss reduction is the main issue for canned switched reluctance machines at high speed. The tooth concentrated windings bring more loss due to harmonics. In this paper, the loss is analyzed and the topology of windings is improved. From MMF distribution theory, a new model and then new type of windings are proposed by increasing the number of layers. Such topology is simple with easy access. As a result, the torque is enhanced while both can loss and iron loss are reduced. Such topology is transferrable to other machines with concentrated windings.

VI. REFERENCES


