Overview of the Rectangular Wire Windings AC Electrical Machine

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(Invited)

Abstract—The rectangular wire winding AC electrical machine has drawn extensive attention due to their high slot fill factor, good heat dissipation, strong rigidity and short end-windings, which can be potential candidates for some traction application so as to enhance torque density, improve efficiency, decrease vibration and weaken noise, etc. In this paper, based on the complex process craft and the electromagnetic performance, a comprehensive and systematical overview on the rectangular wire windings AC electrical machine is introduced. According to the process craft, the different type of the rectangular wire windings, the different inserting direction of the rectangular wire windings and the insulation structure have been compared and analyzed. Furthermore, the detailed rectangular wire windings connection is researched and the general design guideline has been concluded. Especially, the performance of rectangular wire windings AC machine has been presented, with emphasis on the measure of improving the bigger AC copper losses at the high speed condition due to the distinguished proximity and skin effects. Finally, the future trend of the rectangular wire windings AC electrical machine is prospected.

Index Terms—AC copper losses, the rectangular wire winding AC electrical machine, process craft, winding connection.

I. INTRODUCTION

NOWADAYS, the requirement of the machine applying on the traction application is more and more strict in terms of the torque density, efficiency and other electromagnetic performance. The rectangular wire winding AC machine has aroused more and more attention due to their high power density and high torque density, which can become the proper candidate [1]-[3].

Compared with the traditional stranded windings machine, the basic characteristics of the rectangular wire winding AC machine are as follows:

1) Short end-windings, compact structure, and low cost;
2) High slot fill factor and high torque density;
3) Good heat dissipation between the conductor and the slot;
4) Strong rigidity and good steadiness;
5) Low torque ripples and low acoustic noise.

As a result, a lot of outstanding scholars have conducted the detailed research of the rectangular wire winding AC machine including the material, process craft and electromagnetic performance. Different from the traditional stranded windings, the copper conductor cross section area of the rectangular wire windings is much bigger, which means that the choose of the copper materials should pay more attention considering the impact of conductor bending, rebound and the insulation damage. What’s more, depending strongly on the professional manufacturing equipment and complex production craft, there is a huge distinction between the connection of the rectangular wire windings and the stranded windings, where the welding technic has been involved [4]. Thus, it is necessary to reasonably design the connection and guarantee the reliability of the welding and the insulation. Especially, it is found that at the high speed condition the AC copper losses of the rectangular wire windings are much serious due to the distinguished proximity and skin effects, weakening the advantage of the high efficiency, and it is an intractable problem to restrict the bigger AC losses.

In this paper, based on the complex production craft and the detailed electromagnetic performance, a comprehensive and systematical overview on the rectangular wire windings AC electrical machine is introduced. The organization of this paper is as follows. First, the definition and classification of the rectangular wire winding AC machine will be provided in section II. Then, in section III, the craft process, the inserting direction and the insulation type of the rectangular wire winding is discussed, focusing on the difficulties and key points of the production, as well as the machine performance. In section IV, the general connection guideline of the rectangular wire winding has been concluded, combined with the different end-winding connection examples. Next, in section V, the electromagnetic performance and thermal management
between the traditional stranded winding machine and the rectangular wire winding machine has been compared and analyzed in terms of the on-load capability, efficiency and cost, etc. Then, aiming to resolve the bigger AC losses, numerous restricting measures have been provided in section VI. Finally, in section VI, several conclusions are drawn and the development tendency is proposed.

II. DEFINITION AND CLASSIFICATION OF THE RECTANGULAR WIRE WINDING AC MACHINE

A. Definition

Consisted with the new winding structure, the rectangular wire winding AC machine has been quickly developed in recent years due to the superior characteristic, which can be widely used in the electrical vehicle (EV) or hybrid electrical vehicle (HEV) application, such as the Chevrolet Blot 2017 and Toyato Prius IV. Different from the traditional stranded winding machine, which the stator winding is formed by coiling the continuous round wire in slots. The rectangular wire winding machine refers in particular to the stator winding having the different conductor shape, different forming technic, different connection pattern and so on, as shown in Fig 1. And the detailed difference between the stranded winding and the rectangular wire winding has been compared and concluded in Table I.

B. Classification

Among the different production craft and the winding structure, there are two major rectangular wire winding, named as the Hair-Pin winding and the I-Pin winding, respectively, depicted in Fig 2, where one Hair-Pin winding can be considered as jointing two I-Pin windings.

According to the distinctive structure, the preforming craft existing in the Hair-Pin winding can be removed in the I-Pin winding. What’s more, the other production craft including the inserting, welding and twisting are also different. Especially, the Hair-Pin winding machine cooperating with shorter end-winding, compact structure and higher torque density, has been the research hot topic [5]. And the detailed difference between the Hair-Pin winding and the I-Pin winding has been compared and concluded in Table II.

III. PRODUCTION CRAFT OF THE RECTANGULAR WIRE WINDING

In this section, the production techniques in terms of the craft process, inserting direction and the insulation structure have been introduced, which not only have an influence of the production speeds and economic efficiency, but also play an important role in guaranteeing the reliability and performance of the machine.

A. Craft process

Compared with the traditional stranded winding machine, the complexity and the accuracy requirement of production craft in the rectangular wire winding machine have been increased due to using the special materials and winding structure. The detailed production technology of the Hair-Pin winding machine has been researched in [4], with explaining the characteristic of each craft step, as shown in Fig 3, which pointed out that it is the key to keeping the reliability of end-winding welding and insulation. What’s more, the employ of the copper material with the bigger cross section area should take the negative influence of the bending and rebound into consideration. The main process is as follows:

1) Inserting the insulation paper into slots so as to produce the insulation stack, and the different slot insulation structure will be introduced hereafter;

2) Straightening the wire and stripping the paint, where the former aims to eliminate the plastic deformation and the manufacture error, and the latter aims to make the preparation of the conductors contacting such as welding craft;

3) Shaping and forming the wire, which means to produce the forming rectangular wire winding unit that will be inserted in the stator slots. In [6], the detailed forming process has been provided, which can be simply divided into two steps, that is, U-bending and 3-D-shaping;

4) Inserting the forming wire windings into the stator slots,
which the detailed inserting location is determined by the conductor phase per slot, where the star of the slots in the traditional stranded can still be used;

5) Twisting and welding the end of rectangular wire windings. The twisting direction and welding not distribution have a vital impact of the end-winding structure. In [7], the challenges in the manufacturing of hairpin windings and application opportunities of infrared lasers for the contacting process have been discussed.

6) Checking the reliability of the welding and insulation, avoiding the failure occurrence, such as the lack of welding and pseudo soldering. According to the mechanical stress and thermal distribution under different running conditions, an assessment of the machine reliability has been provided in [8]. And in [9], a method of quality monitoring of laser welding in the hairpin windings machine has been introduced.

Compared with the traditional stranded winding machine, the maintainability of the rectangular wire winding machine has been decreased, i.e. once some trouble have been occurred, the overall machine would be damaged. Nevertheless, cooperating with the proper craft, the rectangular wire winding machine has the advantage of high production rate, which is of benefit to mass production.

B. Inserting direction

Relating to the production difficulty, the machine structure and performance, the inserting direction of the rectangular wire windings can be divided into two types, that is, the radical direction and the axial direction, depicted in Fig 4, where the radical inserting direction is same as to the traditional stranded windings which is inserted from the slot opening to the slot bottom. Therefore, limited to the bigger cross section area of the copper conductors, the slot shape of the rectangular wire winding machine is always the parallel slot structure consisting with the open slot, which cause the bigger torque ripples and acoustic noise, as well as deteriorated the AC copper losses.

The axial inserting direction, that is, the inserting direction is from one port of the stator stack steel, named as inserting port, can employ the semi-closed slot structure avoiding the open slot, which is useful to improve the torque ripples, acoustics noise and AC copper losses. However, the twisting can only be accomplished after the rectangular wires have been inserted in the slots, which furtherly raises the production difficulty. In [10], the electromagnetic performance of the machine consisting with the different slot opening shape and different winding structure has been compared and analyzed, shown as Table III.

C. Insulation structure

The insulation performance is the foundation to keep the machine reliability. Considering the complex production craft, some scholars have designed different insulation structure with emphasis on the damage risk during the welding process.
The insulation structure can be classified into three types, i.e. S type, B type and U type, shown in Fig 5, corresponding to Chevrolet Voltec 2011, Chevrolet Spark 2014, Chevrolet Blot 2017, respectively. The S type insulation structure has been gradually phased out due to the existence of the potential safety hazard in the insulation corner. The B type insulation structure has been widely used in recent years due to overcoming the safety problem. Especially, in view of the conductors per slot are on phase where the voltage difference between the conductors can be neglect, the insulation structure between the conductors can be eliminated, which can furtherly increase the slot fill factor and torque density. In [1], General Electric Corporation has invented an insulation structure, where two U type insulation possessing inverse direction has been superposed cooperating with the slot width increase, which has the little influence of the machine performance. Table IV compared the difference among the different insulation structure.

### Table IV: Comparison of different insulation structure

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>S type</th>
<th>B type</th>
<th>U type</th>
</tr>
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<tbody>
<tr>
<td>Amount of insulation materials</td>
<td>Large</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Conductors phase per slot</td>
<td>Custom</td>
<td>Custom</td>
<td>One phase</td>
</tr>
<tr>
<td>Safety degree</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Application example</td>
<td>Chevrolet Voltec 2011</td>
<td>Chevrolet Spark 2014</td>
<td>Chevrolet Volt 2017</td>
</tr>
</tbody>
</table>

IV. THE CONNECTION OF RECTANGULAR WIRE WINDING

The rectangular wire winding machine has applied the special winding connection configuration, that is, the rectangular wire distributed at the non-inserting port has been connected with welding technology. And the corresponding port is named as the welding port. It is important to reasonably design the end-winding structure including the twisting direction and the welding location, which is related to the production difficulty and machine size, as well as the machine reliability and electromagnetic performance. Different from the traditional stranded windings which the coil turns is flexible, the copper conductor number per slot in the rectangular wire winding machine is fixed, which means the number of parallel paths should be more and more possible so as to fulfill the limitation of the inverter voltage and current. Especially, the winding connection should pay more attention to avoid the circulating currents within the parallel paths. Therefore, a lot of works have been done relating to the rectangular wire winding connection configuration.

The different rectangular wire winding connection pattern has been provided in [11], [12], combined with the general design guideline:

1) Determining the slot/pole combination of the stator, the number of conductor per slot, the number of parallel paths and the conductors phase per slot;

2) Determining the connection of the elementary winding, that is, the winding unit having the minimum conductors covered all the layers and all the slots per pole per phase;

3) Determining the coil pitch, twisting direction and the conductor welding relationship according to the elementary winding. Then the detailed winding can be designed and manufactured.

Especially, the end-winding connection diagram of two different elementary windings with four conductors per slot, eight pole pairs and two slots per pole per phase has been drawn in Fig 6 (a) and (b), where the solid line and the dashed line represent the welding port and the inserting port of the stack steel, respectively. It can be seen that the coil pitch of the two winding connection pattern is flexible so as to match the requirement of the elementary winding and guarantee the maximum parallel paths number without the circulating currents.
currents. What’s more, the rectangular wire winding shape, the twisting direction, welding position and the distribution of the outgoing lines are also different. Thus, the production difficulty, cost and reliability of the machine can be improved by considering the winding connection.

The rectangular wire winding machine has been produced in some famous corporations and applied into the EV/HEV application. Remy company has used the end-winding adjacent layer connection, which can be thought as connecting multiple double layer windings, except that jumper lines have been used to stride to different double layer. Different from Remy, Hatichi has invented the end-winding connection, which the conductors distributed at the slot opening and the bottom have been welded into one double layer. The winding connection in Honda Spirior can be considered as dividing all the conductors per slot into one double layer. Toyato Prius has the single layer and double layer hybrid winding connection, where the conductors distributed at the slot opening and bottom have been welded in one layer [13], [14].

The different end-winding connection distributed at welding port mentioned above have been drawn in Fig 7, with 48 slots, 8 poles and 4 conductors per slot, where the three colors represent the three phases, respectively.

What’s more, in order to maintain the stability of the end-winding connection and optimize the distribution of the outgoing lines, some special equipment has been employed, such as the connection ring. In [1], the Chevrolet Bolt stator assembly includes a connection ring for the termination of the phase leads, as shown in Fig 8.

The detailed forming rectangular wire windings possessing different coil pitch, including full-pitch, short-pitch and long-pitch have been comprehensively studied in [15]-[17], with 72 slots, 6 conductors per slot and 3slots per pole per phase, where the end-winding connections have the different types. In [18]-[21], a creative winding stator which can solve the contradiction between the machine size and performance has been given. Furtherly, the type of forming winding and the production cost can be decreased, using the optimized end-winding connection.

In [22], an improved Hair-Pin winding has been introduced, where the end-winding shape has been reasonably designed like the steps, shown in Fig 9, which can avoid the interference between the adjacent end-windings and furtherly decrease the machine size.

V. THE ELECTROMAGNETIC PERFORMANCE AND THERMAL MANAGEMENT OF THE RECTANGULAR WIRE MACHINE

A. Electromagnetic performance

In order to furtherly evaluate the rectangular wire winding machine, the performance of the machine in terms of the on-load capability, efficiency, flux-weakening characteristic and so on, has been systematically researched. In [2], [23]-[26], the electromagnetic performance, production difficulty and the cost of the traditional stranded winding machine and the rectangular wire winding have been compared and analyzed,
shown in Fig 10, where the red line and blue line represent the peak torque and the rated torque, respectively. It indicated that the hairpin winding machine due to the bigger slot fill factor can be the good choice to boost the torque density and power density.

Furthermore, the AC copper losses have also been investigated, the rectangular wire winding having the bigger conductor cross section lead the distinguished proximity and skin effects, which deteriorated the advantage of the smaller DC resistance especially at the high frequency condition. And the detailed DC resistance, AC resistance and total losses have been compared in Fig 11. In [1], the copper losses of the same machine except the different winding structure have been compared, which pointed out that the AC copper losses of the rectangular wire winding machine with 4 conductors per slot would exceed the stranded winding machine when the speed is up to 4000rpm.

The comprehensively design guideline of the high power density rectangular wire winding machine have been given in [27], [28], combined with the optimization of the stator slot opening shape and slot/pole combination, which can achieve the low torque ripples and high efficiency, simultaneously. And the rectangular wire winding machines with the fractional slot and the integer slot have been studied in [29], where the fractional slot distributed winding machine is superior in terms of machine size, efficiency.

For the EV application, the design, optimization and control of the rectangular wire machine have been systematically given in [1], [30], [31], where taking the Chevrolet Spark 2014 and Chevrolet Bolt 2017 as examples, and the comparison of which in terms of the torque density, permanent magnet mass and the overall machine mass has been shown in Fig 12. It can be seen that the development tendency of the rectangular wire winding EV machine is to further enhance the torque capability, as well as decrease the usage of the expensive magnet material so as to reduce machine size and save the cost.

B. Thermal management

The cooling technic is the key to guarantee the machine quality, as overheating will result in degradation of insulation materials, magnet demagnetization and life loss of the machine. Thus, it has drawn more attention to the thermal management of the machine. At present, the water cooling and oil cooling are the two major cooling types of rectangular wire winding
machine. Especially, the spray oil cooling at the end-winding has been applied in the Chevrolet Voltec, depicted in Fig 13, which can dramatically improve the heat dissipation and enhance the torque density due to the bigger rectangular wire winding interval compared with the stranded winding [32].

VI. THE RESTRICTION OF THE AC COPPER LOSSES OF THE RECTANGULAR WIRE WINDING MACHINE

Considering the disadvantage of the AC bigger copper losses of the rectangular wire winding machine at the high speed condition, a lot of outstanding works have been done.

First, in order to investigate the origin of the AC copper losses, the relationship between of the machine structure parameters and the copper losses have been studied [33]. Especially, some detailed models employing either numerical and analytical approaches have been built to predict the AC copper losses [34]-[39].

The eddy-current losses and thermal analysis of an inverter-fed cage induction machine with a multi-conductor stator winding have been presented, which pointed out the installment of the magnetic wedges at the slot opening is a simple way to reduce the eddy-current loss [40]. And the influence of the air gap size and the winding position on the copper losses has been researched, which indicated that increasing the distance between the winding and the air gap can improve the copper losses. And based on the foundation that the AC copper losses at the slot opening is serious, positioning the conductors near the slot bottom, reducing the slot opening size and applying the transposition method can reduce the copper losses effectively[41-42]. What’s more, the conductors shape has also an impact of the AC copper losses [43], shown in Fig 14.

However, the model mentioned above is the 2-D neglecting the end-winding copper losses, the influence of the end-winding size on the proximity in high speed machine has been provided in [44].

In view of the conductor layer number per slot, the related research has been carried out, which pointed out that the increase of the conductor layer number can significantly decrease AC copper losses so as to improve the machine performance at the high speed condition. In [1], the AC copper losses of Chevrolet Spark 2014 and Chevrolet Bolt 2017 have been compared, using 4 conductors and 6 conductors per slot, respectively, where the diagram of the conductors distribution and the copper losses are depicted in Fig 15 and Fig 16.

Furthermore, some scholars have found that the conductors phase per slot has a vital impact of copper losses in [45]-[48], where six different conductor phase arrangements have been compared with 4 conductors per slot, shown in Fig 17, which indicated that conductor phase arrangements of ABAB and ABBA have the minimum AC copper losses. However, the conductor phase arrangement of the same phase has the most serious condition. Thus, it is necessary to reasonably design the
winding connection taking the AC copper losses into consideration.

In [49], an optimal twisting criterion has been proposed which achieved the minimization of the copper losses due to parasitic circulating currents and reduced the number of twists and the length of the coils.

In [50], hybrid rectangular bar windings consisting of copper bars which are located close to slot bottom and aluminum bars which are located close to the slot opening have been introduced, which can not only decrease the copper losses, but also reduce the machine mass, shown in Fig 18.

VII. OPPORTUNITY AND CHALLENGE OF THE RECTANGULAR WIRE WINDING MACHINE

A. Opportunity

In order to resolve the environment pollution and resource shortage, the focus on the EV/HEV has been dramatically increased in recent years due to the superior performance, where the traction machine is the core of the vehicle. Limited to the slot fill factor, heat dissipation and machine cost, the traditional stranded winding machine can seldom achieve the requirement of the higher torque density and higher efficiency. However, the rectangular wire winding machine can be the optimal replacement due to the good electromagnetic performance. At the same time, a lot of famous models have employed the rectangular wire machine and mass production, which proved the vast development potential.

B. Challenge

Although the more attention has been paid to the rectangular wire winding machine, there are still some problem waiting to be researched, which are described as followed:

1) Improving the production craft. It is the key to guarantee the accuracy and reliability of production technology, which decided the machine safety and performance. What’s more, combined with mature craft, the mass production and launching to the market can be achieved.

2) Optimizing the winding connection. At present, the winding connection of the rectangular wire winding has seldom been researched in terms of the different conductor number per slot, different slot/pole combination and different parallel path number. And the difference and relationship among different end-winding connection, cost, production difficulty and reliability has seldom been given.

3) Reducing the production cost. It can be seen that the production of the rectangular wire winding is complexity which strongly depended on the expensive professional equipment. Thus, it may be one of the constraints that restricting the development of rectangular winding machine. However, with the full automation and mass production, the cost can be reduced.

4) Restricting the AC copper losses. Although a lot of works have be done using different methods to reduce the copper losses, it would cause the bad influence of other characteristic of the machine such as increasing cost, torque ripples and torque density. Thus, it is valuable to investigate the more effective measure to optimize the losses, save cost and boost the efficiency.

VIII. CONCLUSION

This paper has presented the overview of the rectangular wire winding machine with a focus on the production craft and electromagnetic performance. What’s more, the winding type, inserting direction, insulation structure and winding connection have been researched, combined with the production technology. Furthermore, the electromagnetic performance and thermal management of the machine having the different winding structure have been compared and analyzed, which indicated the superior characteristic of the rectangular wire winding machine that satisfies the requirement of the EV/HEV application. Especially, in view of the weakness of the bigger AC copper losses, some methods have been provided so as to furtherly improve the machine efficiency. In a word, the rectangular wire winding machine has the vast development prospect due to the high torque density, high power density and so on.
REFERENCES


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