

Advanced Conductor Shape Technology

Оптимизиране формата на секция от правоъгълен меден проводник намираща приложение във статорите на хибридните двигатели

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Abstract: *The aim of the project is to analyze the possible section geometries of stators for starter generators and to select the most effective geometry for use in practice. The experimental results showed the benefits of the "S"-shape conductor compared with "P" or "U"-shape.*

Keywords: CONDUCTORS, HYBRID STATORS, BASKET OF STATOR.

Problem Relevance

The world's leading automotive manufacturers constantly thrive to improve fuel economy. This has taken automobile production in a new direction – the introduction of hybrid vehicle. It has been proven that a hybrid automobile can reduce fuel consumption by up to 50% when compared to conventional engine powered vehicle. The idea is not entirely new however its realizing has seen several major hurdles in the way: very high cost of production for the batteries and the requirement for highly effective (high capacity) starter-alternators. The rapid development of modern technologies managed largely to solve the problem with the batteries. Automotive manufacturers are currently working hard to develop highly efficient starter-generators. In order to increase the starter-generators efficiency, one must first optimize the stator design. This is where the possibilities of increasing efficiency are the greatest.

M3D, a machine manufacturing company, has vast experience in developing machines and technologies that have superior applications in the production of starters and generators. The company has produced machines which operate in some of the world's best automotive producers, such as Bosch and Valeo-Europe, Delco and Prestolite – USA, Denso and Mitsubishi – Japan. By combining the theoretical and experimental experience of the Institute of Metal Science, Equipment and Technologies with Hydro- and Aerodynamics Centre "Acad. A. Balevski" at the Bulgarian Academy of Sciences and with the technological experience of M3D, we have been able to create a setting for ultimate success with these developments.

The thesis of the following research is to create a conductor with new geometry which will improve the stator characteristics.

Problem analysis

The classic generator-stator with coils made of round conductors is technically obsolete, mainly due to the coefficient of filling the stator slot with a round conductor is smaller when compared to a conductor with a rectangular section. This is the reason why all hybrid stators nowadays use only rectangular conductors. Optimizing the conductor geometry of such conductors can indeed help increase the stator efficiency. The purpose of optimizing the geometry of the conductors is for them to form a basket (which is a collection of the conductor heads pointing in the opposite direction of the stator-side outlets/terminals) after being inserted in the stator core (body). The basket should have minimal dimensions, however, the hairpins shoulders should not come into contact with each other. The other condition that must be met is the distance $W1 \leq W3$ (fig. 1). With the upper limits in mind, it is necessary to optimize the shape of the conductors, so that the optimum density of the basket can be achieved, with maximum possible airflow between conductors. This requirement has been formed under one highly important condition – the need for achieving optimal cooling of the stator, for the purpose of reducing heat created in the stator, which can result in over 30% efficiency loss.

The current work process utilizes a 3-dimensional method of shaping the conductor head, i.e., realizing deformation along 3 axes – moving the pin, which allows bending along the X-axis, twisting along the plane of X and Y, as well as controlled positioning of the movable conductor shoulder in the direction of the Z-axis (fig 2.1). Applying deformation in the Z-axis is realized for the first time, but as the following results will show, it is of paramount importance. This deformation helps to control

the shoulders slope in the crown, and thus helps to achieve maximum airflow between the crowns of conductors, in other words the best cooling in the coil.

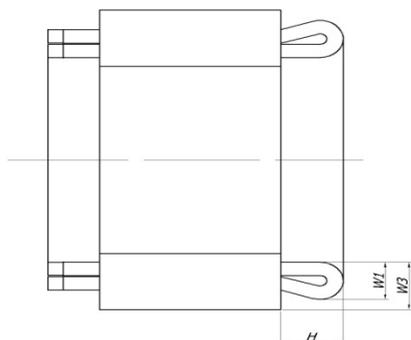


Fig.1

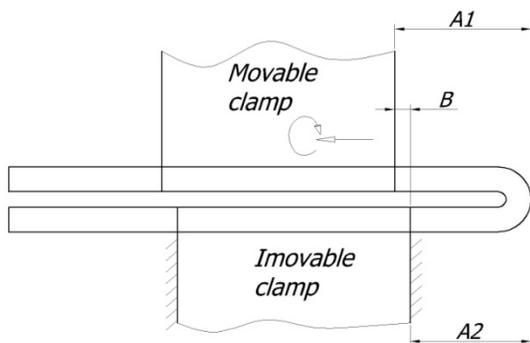


Fig.2.1

Theoretical and experimental methods of solving the problem

A combined approach was used in the experiment optimization – experiments paired with mathematical and computer methods for simulation. The entire forming process can be simulated with the help of specialized software. After which, full analysis of the advantages and disadvantages of each conductor shape can be made. For instance, for “U”-shape of semi-complete conductors, it can be visualized how the final desired form is achieved (fig. 2.2 and fig. 2.3). These results are obtained by experimentation as the mechanical characteristics for copper conductors with precise dimensions were entered in the software. The software also helped in achieving deformations, as well as the spread stress amount in every part of the conductor during the forming process. The

software further permits yet another step, which is inserting the deformed conductor in the stator body and to visualize the basket. This approach enables us to seeing the placement of the conductors in the stator slots, and to also check how they are arranged in the stator basket. This allows us to deduct whether the angle of twist in the last technological step needs to be adjusted and by how much. Following this sequence, the desired geometric parameters of the section are achieved after several iterations.

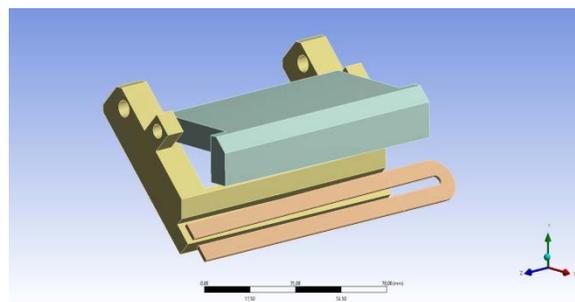


Fig.2.2

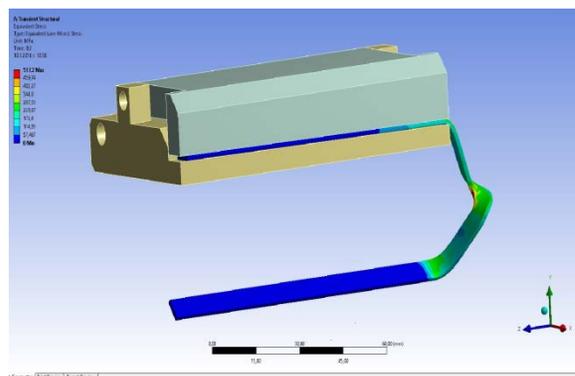


Fig.2.3

Experimental results

Practice shows that three important parameters related to the conductor geometry and forming the stator basket must be taken into consideration during the forming of the conductors.

The distance between two adjacent shoulders of conductors forming the basket. Figures 3 and 4 show the shoulder shape in the basket. In this case “P”-shape and “S”-shape can be seen. In the case of “P”-shape, the shoulders are part of the horde, whereas with “S”-shape, the shoulders are rainbow shaped. If the angle of twist of the “P”-shape is large enough, then there is a high possibility that the outside shoulder will touch the inside shoulder. This is the main reason for the high risk of shorting in this area. To avoid this problem, especially with bare conductors,

manufacturers that use "P"-shape sections are usually forced to place an insulating tape between the inside and outside conductor shoulders. This is a highly labour-intensive method and because of that has limited application.

space between two neighbouring shoulders is usually larger in the outside row than on the inside row (fig. 6).



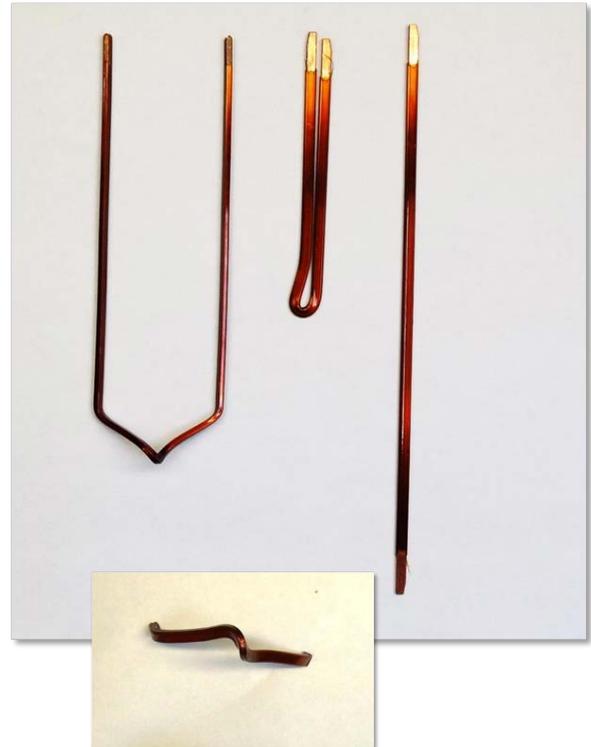
"S"- form

Fig.3

Another way to avoid this problem is by increasing the pin diameter, where a process known as U-bending is applied. This, however, leads to a different problem – increasing the height of the crown ($H_1 > H$) (fig. 5). As of this reason, the idea has limited application, due to the likelihood of insufficient space. As Figure 5 shows, using an "S"-shape conductor is the solution.

Several problems that require a solution occur in shaping the basket:

-Contact between two adjacent shoulders in the basket. This is a fairly common problem for conductors with small crown height. After twisting is applied, the



"P"- form

Fig.4

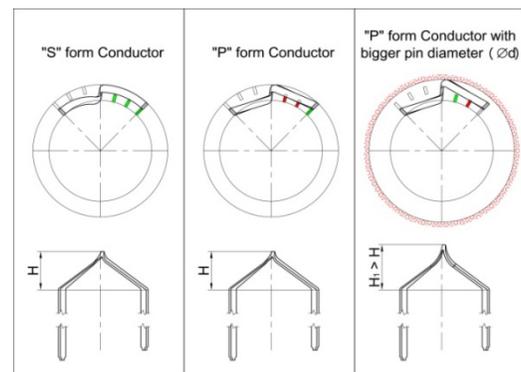


Fig.5

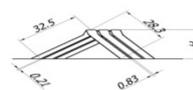


Fig.6

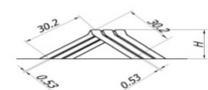


Fig.7

In order to achieve even distances between the adjacent inside and outside shoulders, it is necessary to alter the length of the shoulders in the crown by means of moving in the direction of Z-axis (fig. 2.1). These distances can be made equal by varying the magnitude of movement "B", if all other parameters remain unchanged. It should be noted that this can be achieved without having to change the height of the crown "H".

-Controlling the interior and exterior diameter of the stator basket. The possible amount of control is limited for "P" and "U"-shape conductors. It is possible with "S"-shape sections by shifting the section axis of symmetry in the direction of the X-axis (fig. 8).

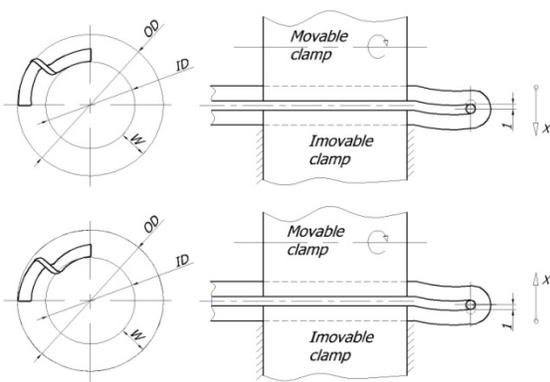


Fig.8

As the figure shows, if during the process of forming the pin around which the twisting occurs, it is positioned in the direction outside the axis of symmetry of the semi-complete conductor (for example, by 1mm as shown in the figure), the interior and exterior diameter of the basket will increase. If the pin is moved in the opposite direction, i.e. towards the axis of symmetry, then the interior and exterior diameter of the basket will decrease. Fine adjustments to the height of the basket can be made using that method. This cannot be applied in the case of "P"-shape, because the axis of symmetry and axis of rotation must coincide.

The production technology of "S"-shape (fig. 9) looks similar to that of "P"-shape, but only seemingly, which is apparent in the big difference in the final shape of the conductor crown. By changing the radii "R" and "r" in step 2, the desired arcs can be set. The above described steps can be visualized with the help of the software. This software can simulate the entire technological process, and thus can analyze the effect of every separate parameter involved in the forming of the conductor. As can be seen in the case of "P"-shape, the distance between the inside shoulders of two adjacent conductors is very small (fig. 10). This is the reason for probably shorting with "P"-shape. As the figure depicts, this effect is increased when the angle of twist grows. If the angle of twist is 20 degrees, the distance between the inside shoulders is sufficient, whereas if the

angle is increased to 45 degrees, the risk of shorting is much higher. The experimental results show that the problem is completely eliminated by utilizing "S"-shape conductors (fig. 11).

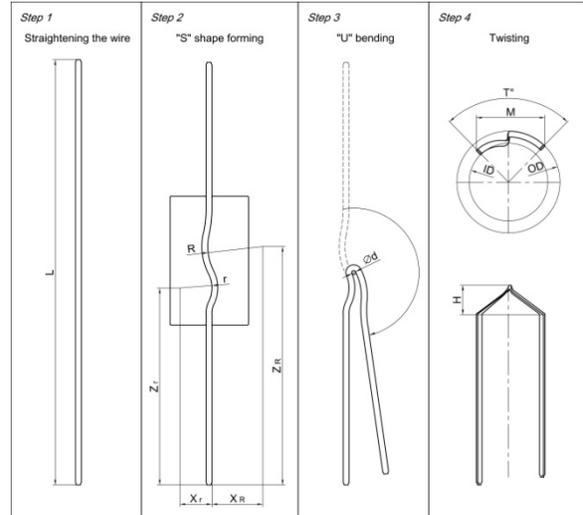


Fig.9

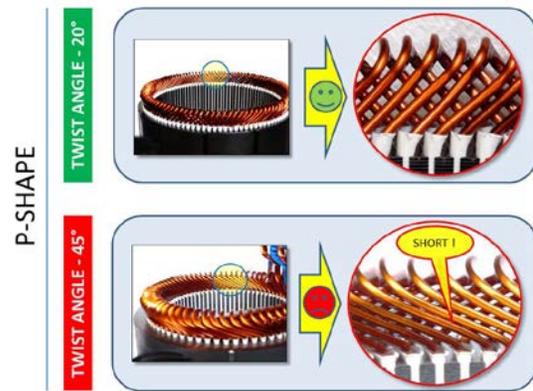


Fig.10

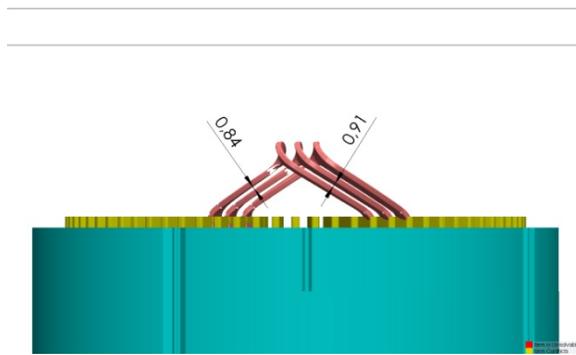
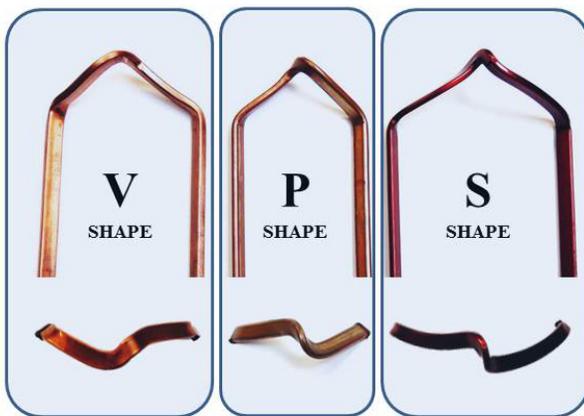


Fig.11



Analysis of the results

We will conduct the experiment to allow us to compare the advantages and disadvantages of the common technologies for conductor forming (table 1).

Productivity: for “V”-shape conductors – it is lowest in comparison with all others, because all production steps are carried out successively in time (score – 1 point).

Repeatability of the conductor crown: “S”-shape conductors have high repeatability (score – 3 points), whereas “P”-shape conductors have low repeatability (score – 2 points), because the conductor crown is freely formed during the time twisting process.

Optimal marker dimensions of the conductor crown: only the “S”-shape section allows for fine adjustments of the crown dimensions (score 3 points).

Airflow: minimal airflow in the basket can be observed in the case of “P”-shape section, because the slope of the crown shoulders cannot be controlled (score – 1 negative point). This problem can be solved by applying additional shifting in the direction of the Z-axis.

Practice shows that only “S”-shape can fully optimize the gauged dimensions of the basket and ensure minimal basket width (score – 3 points).

Minimal crown height can be achieved using the “V”-shape conductor (score - 3 points).

“P”-shape has a high risk of shorting in the crown shoulders (score – 1 negative point).

“V”-shape does not allow for any corrections in the crown shape (score – 1 negative point).

“V”-shape is not suitable for varnished conductors because it can easily damage the insulation (score – 1 negative point).

The total scores show the benefits of “S”-shape conductor in comparison with all other section types – 27 points (table 1).

Tabl. 1.

| | “V”-SHAPE | “P”-SHAPE “U”-SHAPE | “S”-SHAPE |
|---|-------------|------------------------|-------------|
| 1. Productivity | + | +++ | +++ |
| 2. Crown shape consistency | +++ | ++ | +++ |
| 3. Optimum overall crown dimensions | ++ | + | +++ |
| 4. Maximum air flow through the winding | +++ | - | +++ |
| 5. Minimum winding width | ++ | + | +++ |
| 6. Minimum crown height | +++ | ++ | +++ |
| 7. Risk of short in the winding | ++ | - | +++ |
| 8. Crown shape adjustment | - | ++ | +++ |
| 9. Enameled wire | - | +++ | +++ |
| BALANCE | 14 + | 12 + | 27 + |

CONCLUSION

The experimental results show that the proposed “S”-shape has significant benefits when compared to all other conductor types.

We can conclude that the new highly effective “S”-shape conductor and the technology used for its forming can find applications not only in the hybrid, but also in the conventional engines for the automotive industry.