

# Variable cross-section windings for efficiency improvement of electric machines

**P Yu Grachev<sup>1</sup>, A A Bazarov<sup>1</sup> and A S Tabachinskiy<sup>2</sup>**

<sup>1</sup>Professor, Samara State Technical University, Samara, Russian Federation.

<sup>2</sup>PhD student, Samara State Technical University, Samara, Russian Federation.

Tabachinski.as@ieee.org

**Abstract.** Implementation of energy-saving technologies in industry is impossible without efficiency improvement of electric machines. The article considers the ways of efficiency improvement and mass and dimensions reduction of electric machines with electronic control. Features of compact winding design for stators and armatures are described. Influence of compact winding on thermal and electrical process is given. Finite element method was used in computer simulation.

## 1. Introduction

The serious problem of efficiency improvement of electromechanical converters is often solved by implementing advanced control algorithms, which are able to afford process quality without any changes in power converter construction [1].

In the Ural region, some researches of construction development for electric machines were made recently [2,3]. The aim of the researches was to improve efficiency and reduce mass and dimensions.

For vehicles application, in Japan special stator construction of starter-generator was proposed [4]. This construction includes rectangular winding wires that are able to reduce overhang deviation and copper intensity.

Even greater efficiency improvement and dimensions reduction of autonomous power units, hybrid (HEVs) and electric vehicles (EVs) in particular, can be reached by multipolar machine and multiphase electronic converter integration. In Germany, alternating current machine with short-circuited stator winding and integrated electronic converter is approved [5]. Electronic converter can change virtual number of machine phases during the operation, which leads to increased output performance of power unit. Extra-low operating voltage is the disadvantage of this AC machine.

The researches of integrated power units for hybrid vehicles, wind turbines and micro-hydro are holding in Samara [6]. The AC machine construction with compact windings leads to significant reduction and overhang deviation, mass and dimensions, both with efficiency improvement. The main idea of winding construction is in periodical variation of rectangular conductor cross-section [7,8,9]; this construction allows varying air gap between stator core and overhang parts, as well as overhang deviation.

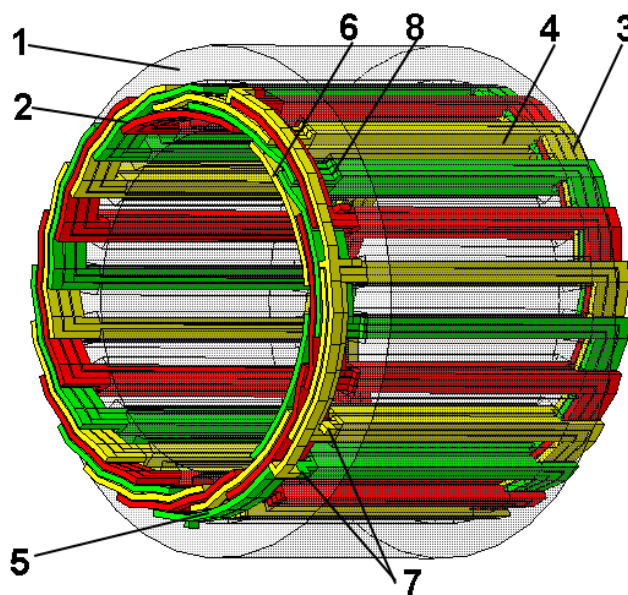
In this article, construction features of compact windings for DC and AC machines are described. In windings with irregular cross-section irregular current density is observed [10]. The results of computer simulation of electromagnetic and thermal fields that are given in the article allow to measure phase resistance and temperature in active and overhang parts, as well as to design material-



saving construction [11]. Construction features of compact winding can be used in other types of electric machines [12].

## 2. Machine stator with irregular cross-section winding

Let us consider construction features of this winding. On figure 1 stator with three-phase rectangular concentrated winding and series connected branches is illustrated. Winding phase consists of three branches. Overhang parts of compact winding are parallel to stator core end-faces. There are jumpers between overhang and active conductors, and jumper cross-section is less than others. This allows to place overhang parts in the same plane without overlapping [8].



**Figure 1.** Electric machine stator with compact winding.

On figure 1 we can see: 1 — stator core, 2 — winding, including active parts 3 and overhang parts 4. Overhang conductors 5, placed near the core yoke, connect branches of the winding phases. Overhang conductors 6 near the air gap connect half-branches. Phasing outs 7 are connected with active conductors of the bottom layer. Cross-section of jumpers 8 that connect active and overhang conductors is double reduced. This allows to significantly decreasing the overhang deviation.

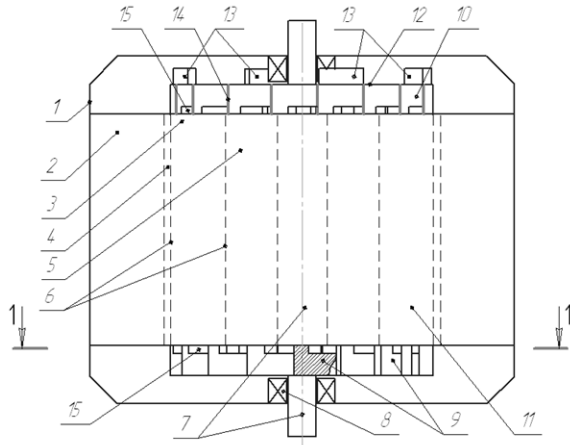
From the other end-face there are no phasing outs and branches connection. Overhang construction does not depend on winding scheme and branches connection. Jumpers from this side has also reduced cross-section and the deviation is also decreased.

Due to winding length reduction, active power losses are decreasing and efficiency is increasing. Volume reduction is extremely important for autonomous application, like electric vehicles and wind turbines, because of the strict dimensions requirements. Nevertheless, for new form of overhang conductors, which allow to vary air gap between stator core and overhang conductors, new electrical and thermal processes should be considered [11]. It is very important to research the dynamic processes of compact winding machine, for example, for start processes of internal combustion engine of hybrid vehicles [13].

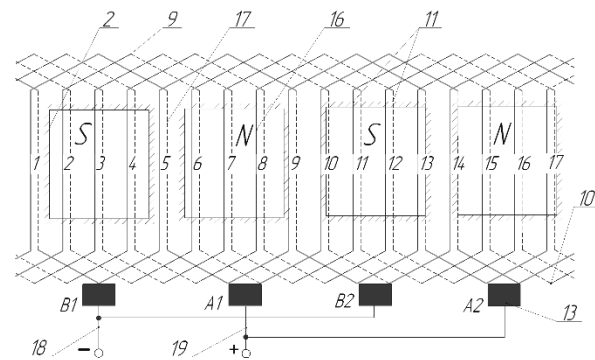
## 3. New winding for DC machine armature

On figure 2 composition of brushed DC machine with new armature winding construction [14]. In the housing 1 stator 2 is placed, generating the stationary magnetic field. Stator consists of yoke and pole with field windings. Armature 3 divided from stator 2 by air gap 4, and consists of armature core 5

with slots 6 (marked by dashed line). Armature is placed on shaft 7 and rotating on the bearings 8. Armature winding has two layers and includes overhang conductors 9 and 10 from both end-faces and active conductors 11. Outer parts of overhang conductors 10 play the role of slip rings 12 of commutator. Commutator also includes carbon brushes 13. Overhang insulation 14 also insulates slip rings of the commutator. Air gap 15 improves air convection for better cooling of overhang parts.



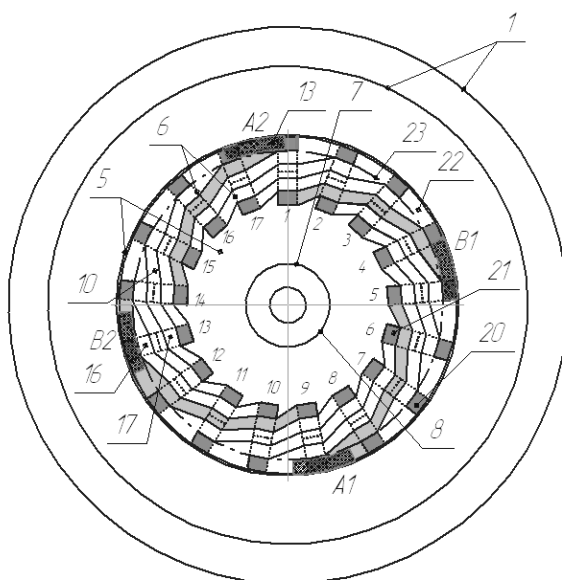
**Figure 2.** Composition of DC machine with compact armature winding.



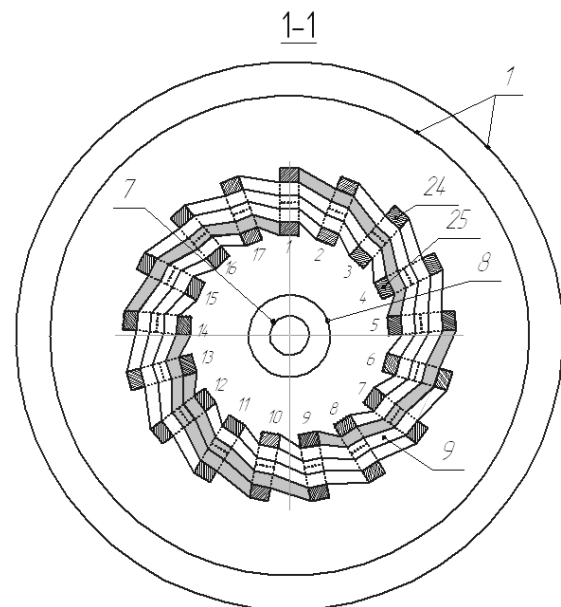
**Figure 3.** Winding scheme of armature.

On figure 3 armature winding scheme for this DC machine is illustrated. Wave bar winding has number of poles  $2p=4$ ,  $Z=Z_E=S=K=17$ ,  $y_1=4$ ,  $y_2=4$ ,  $y_k=8$ . Stator poles marked with N and S. Solid lines illustrate active conductors of the upper layer 16, and dashed lines — bottom layer 17. We can also see overhang conductors 9 and 10. Brushes A1, A2, B1 and B2 connected to power supply bus 18 and 19.

On figure 4 top view of DC machine armature is illustrated. On figure 5 cross-section 1-1 from figure 2 is illustrated.



**Figure 4.** End-face composition of considered DC machine.



**Figure 5.** End-face cross-section of considered DC machine.

Housing 1 is transparent. Rectangular slots 6 of armature 5 are numbered clockwise. In the slots active conductors (bars) of upper 16 and bottom 17 layer are placed. They are connected to each other by overhang conductors 10. As we can see, jumpers 20, 21 between active and overhang conductors have reduced cross-section (marked with grey) — for this particular case cross-section of jumpers is 2/5 of active conductor cross-section. Jumpers are placed on the outer sides of active armature zone. This zone includes slots with active conductors and teeth and was described by Inkin A.I. in [13].

On the figure 4 we can see, that a part of each overhang conductor 10 is made like slip ring 12 with smooth surface 22 for commutator. Slip ring is bordered by dashed circle 23 and outer side of overhang parts 10. Brushes 13 are marked with hatched area.

Construction of overhang parts 9 and 10 is equal. On figure 5 jumpers 24 and 25, connecting active conductors with overhang conductors, are illustrated.

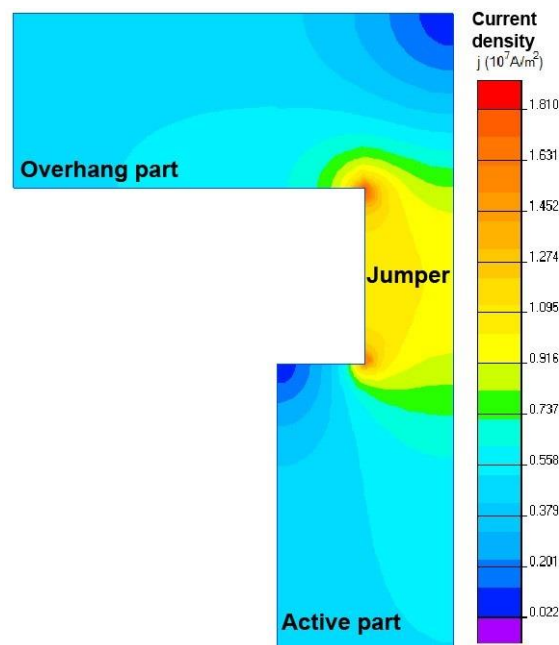
Proposed brushed DC machine operates like serial brushed DC machine with stationary stator.

Thus, new patented compact construction of DC machine allows to replace typical commutator with integrated slip ring on the overhang conductor surface. This leads to mass and dimensions reduction and improvement of efficiency.

#### 4. Electrical processes in the winding

Overhang parts shape, made like slip rings over the stator core end-faces, imposes the use of Ohm's law in integral and differential form [15]. Experimental [16,17] and theoretical [18] researches of current flow in flat conductors were made. Complex construction of winding turns features calculations of overhang deviation and phase winding parameters.

Calculation of phase resistance considers irregular current density for reduced cross-section conductors. On figure 6 finite element method was used in ELCUT 5.1 for current density simulation of compact winding.



**Figure 6.** Current density in compact armature winding.

Results of simulation have shown that irregular current density influences resistance calculation only for short active zone length ( $l < 0.5D$ ). For longer active zones simplified methodic of phase resistance calculation is proposed [10]. In case of serial machine design, irregular current density consideration specifies resistance calculation for less than a percent.

## 5. Efficiency calculation

From the figure 1 for another 24-slot stator of AC machine we can see 4 overhang conductors over the slot area, two of them are placed in the free space and two of them are connected by jumpers with active conductors. Thus, for this particular winding overhang conductor width can be calculated:

$$b_o = \frac{h_s - 2h_j}{n} \quad (1)$$

here:  $b_o$  – overhang conductors width with insulation;  $h_s$  – height of all active conductors in the slot with insulation;  $h_j$  – jumpers height (in this case half of active conductor height);  $n$  – number of overhang conductors over one slot (depends on coil span).

Height of overhang conductor, in case of cross-section equality with active conductors, is:

$$h_o = \frac{S_s}{b_o} \quad (2)$$

here:  $h_o$  — overhang conductor height with insulation,  $S_s$  — slot conductor cross-section.

On the figure 1 three overhang conductors in a group, one over another, could be seen. Number of branches in a phase defines number of overhang conductors in a group. For this particular case, overhang deviation with air gap  $\Delta$  is:

$$l_{OD} = 3h_o + \Delta \quad (3)$$

Calculations have shown the advantages of compact winding construction: for 80mm shaft height generator 4AN80A8U3 with rated voltage 220V, overhang deviation reduces from 29.8 to 12.7mm, active core length reduces by 20%, copper intensity reduces by 16.2%, and efficiency rises from 92% to 94%.

## 6. Thermal processes in the machine

For thermal flow calculation in stator the next 3D mathematical model is given:

$$\frac{\partial T(r, x, t)}{\partial t} = \nabla \cdot (k \nabla T) + \frac{1}{c\gamma} Q(x, y, z, t) \quad (4)$$

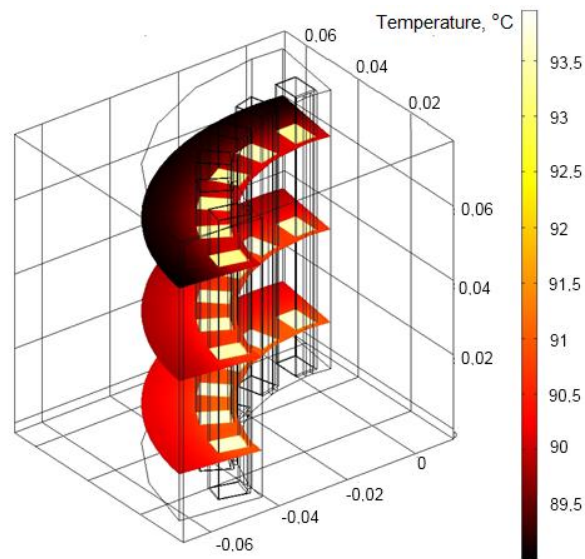
with border an initial conditions:

$$\begin{cases} T(x, y, z, 0) = T_0 = T_c; \\ n \cdot (k \nabla T) = \alpha (T - T_c); \end{cases} \quad (5)$$

here:  $n$  – normal vector to the surface of computational area;  $c$  – specific heat capacity of steel, conductors and insulation;  $\gamma$  – density of steel, conductors and insulation;  $\alpha$  – heat transfer coefficient;  $k$  – thermal conductivity of steel, conductors and insulation;  $Q(x, y, z, t)$  – distribution function of inner heat sources.

Finite element method was used to calculate temperature distribution in stator core and active conductors for different air gaps between stator core and overhang conductors [10,13]. One case of temperature distribution is illustrated on figure 7.

For small air gap between stator core and overhang parts, temperature of overhang conductors rises. In every group of overhang conductors thermal condition of different levels varies. Overhang conductors can have common insulation for better heat transfer. Air gap needs to be wider for better air convection and heat transfer between overhang parts and stator active zone.



**Figure 7.** Stator core temperature distribution for 60A phase current and 2mm air gap.

Temperature distribution for wider air gap in active and overhang parts was researched. The results are given in table 1. This results allow to consider that wider air gap strives to equality of active and overhang conductor temperatures. But overhang deviation also increases.

Other cooling systems for these machines are scheduled to research. Frequency rotation control [20,21] and vibration consideration [22], for example.

**Table 1.** Temperature of active and overhang conductors.

№	Heat transfer coefficient, $W/(m^2 \cdot ^\circ C)$		Active conductor temperature, $^\circ C$		Overhang conductor temperature, $^\circ C$	
	Stator end-face	Overhang parts	min	max	min	max
1	30	29	107	109	108	109
2	30	35	98.8	101	99.1	100
3	30	39	86.8	88.9	86.8	87.7
4	60	43	73.5	75.8	72.8	73.6
5	60	29	90.3	92	89.8	90.3

## Conclusions

1. Proposed compact winding construction for DC and AC machines with periodical variation of conductor cross-section allows to decrease overhang deviation, reduce copper intensity and improve efficiency.



2. Research of irregular current density in compact winding was held via finite element method and computer simulation. The results have shown negligible effect of irregular current density on phase resistance and temperature of conductors and insulation.

3. Methodic of machine design with compact winding was given. The methodic considers features of compact winding construction.

4. Research of thermal processes in compact winding have shown the necessity of common insulation for overhang conductors for temperature gradient reduction. For improvement of heat transfer and decrease of overhang temperature air gap between stator core and overhang parts needs be increased. These decisions will make possible to increase maximum power of the machine.

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