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Influence of winding construction on starter-generator thermal processes

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Abstract. Dynamic processes in starter-generators features high winding are overcurrent. It can lead to insulation overheating and fault operation mode. For hybrid and electric vehicles, new high efficiency construction of induction machines windings is proposed. Stator thermal processes need be considered in the most difficult operation modes. The article describes construction features of new compact stator windings, electromagnetic and thermal models of processes in stator windings and explains the influence of innovative construction on thermal processes. Models are based on finite element method.

1. Problem Statement

For vehicles application mass and dimension reduction of electric equipment is strongly relevant. In hybrid vehicles, starter-generator, based on induction squirrel-cage machine, is applied [1]. Original stator construction of electric machine for HEVs is designed [2]. It allows to decrease overhang deviation and reduce copper intensity due to rectangular cross-section stator conductors. Greater dimensions reduction can be achieved in case of multipolar induction machine integrated with multiphase semiconductor converter [3, 4]. Electric machine in [3] has squirrel-cage rotor and stator windings. Suggested electric drive based on this electric machine, has real-time control of phase number and wide speed range. However, small number of turns per phase defines extra-low voltages.

Mass and dimensions reduction is also relevant for aviation [5]. Integration of electromechanical converters and engine is prospective. Electric machines operates at high temperatures and rotation speed. Here, as well as in combined power units for HEVs and EVs, attention is paid to cooling system of power converters [6, 7].

Significant dimensions and overhang deviation reduction is able in innovative stator compact winding construction. This winding has rectangular irregular cross-section conductors [8, 9]. Construction feature defines irregular current density in parts with reduced cross-section. Irregular current density influences phase resistance [9]. Improvement of dynamic modes increase starting currents in these electric machines [10]. It needs be considered in electromagnetic and thermal calculation of electromechanical converters.

In fig. 1 time diagrams of HEV internal combustion engine (ICE) start process is illustrated. Startergenerator rated power is 15 kW, and its power supply is 144 V DC source. Induction machine replaces flywheel on the ICE crankshaft.

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Figure 1. Frequency start of ICE time diagrams.

In fig. 1a variations of electromagnetic torque M, crankshaft torque M_{st} , rotation frequency n and absolute slip *Beta* are illustrated. In fig. 1b valve converter input voltage U_d and DC source current I_d are illustrated. For start torque 450 Nm, DC source current I_d reaches 400 A. Stator phase current reaches maximum rating in the first moment of start process, and winding temperature rises rapidly. Insulation aging is significant at high temperatures. Thus, to improve reliability of electric machine in start/stop processes for HEVs and EVs, precise thermal simulation is needed [11].

This article focuses on thermal simulation and calculation for innovative induction machines as parts of autonomous power units. Innovative construction allows to reduce dimensions and improve efficiency, and is protected by patent [8]. Fig. 2 illustrates stator of innovative induction machine.





Let us consider the features of the construction. Stator winding is three-phase and conductors are rectangular cross-section. Each phase is divided on three branches. Overhang parts of compact winding are parallel to stator end-faces. Connection spots of slot and overhang parts has double reduced cross-section. This solution allows to place overhang conductors of different slots in the same layer.

Fig. 2a illustrates compact winding stator end-face with phase outs. The winding in this machine is wave and concentrated, and the branches are connected in series. On the figure, position 1 points conductor, connecting branches of the winding. Pos. 2 points phase outs, connected with slot conductors of the upper layer. Pos. 3 points connection of half-branches. Pos. 4 points connection spots of slot and overhang parts. There is a small air gap between overhang parts and stator end-face. Overhang deviation is significantly reduced.

Fig. 2b illustrates opposite stator end-face. This is the side without phase outs. Overhang conductors connect slot conductors with each other. Overhang construction does not depend on branch connection order.

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Due to length and resistance reduction, power losses in stator winding also decrease. Overhang deviation reduction decrease total length of the electric machine, allowing to apply machine in limited space of HEVs and EVs. Nevertheless, irregular cross-section of stator conductors influences thermal processes in stator [12]. This needs be considered especially in dynamic modes, start/stop processes of hybrid and electric vehicles, for example.

In this article, thermal processes for different air gap value between overhang parts and stator endfaces are considered. Research is made for induction squirrel-cage machine with compact stator winding.

2. Theoretical Basement

For electromagnetic and thermal research in electromechanical converters, finite element method is suitable [13, 14].

For 2D flat model, electromagnetic field is described by equation:

$$j\omega\sigma\mathbf{A} + \nabla \times \left(\mu_0^{-1}\mu_r^{-1}\nabla \times \mathbf{A}\right) - \sigma\mathbf{v} \times (\nabla \times \mathbf{A}) =$$

$$= \left(\frac{\sigma\Delta V}{L} + J_z^e\right) e_Z \cdot \mathbf{A} = A_z e_z$$
(1)

here: J_z^e – current density; **v** – rotor velocity vector; σ – conductivity; A – magnetic vector potential; μ_0 - magnetic constant; μ_r - relative permeability; ΔV – potentials difference on the conductor ends; *L* – conductor length by the Z axis; ω – cyclical frequency.

Zero magnetic potential on the distant border of computing area is the boundary condition:

$$A_7 = 0 \tag{2}$$

Difference between magnetic circuits of rotor and stator is considered with B-H curves.

Definition of limit operation modes, when the conductors and the cores of stator and rotor are not overheated, is one of the design issues [15–22]. For this reason, internal heat sources in stator and rotor conductors are calculated in electromagnetic problem. In squirrel-cage conductors current frequency depends on slip; this leads to skin effect and increased power losses in conductors. Heat sources definition in overhang parts of stator winding is another issue. Broken magnetic circuit gives another current density condition, despite of small conductor dimensions. Even if current penetration depth exceeds conductor cross-section, current density and heat dissipation density conditions vary a lot.

Thermal processes calculation faces problems, concerned with heat transfer coefficient definition between stator and rotor construction and air [23–26], as well as thermal conductivity of multi-layer insulation and air gaps. Heat transfer coefficient is defined in hydrodynamic problem of air transfer inside the housing, or by theoretical calculation within proper criteria. Air gap can be easily taken into account in mathematical model, but in practice air gap depends of many different circumstances, such, as vibration, assembly quality, etc.

The following terms influence induction machine cooling condition:

- 1. Forced cooling provides air flow and improves heat convection in overhang parts.
- 2. Reduction of gap between overhang parts and machine housing increases air flow resistance and reduces heat transfer.
- 3. Overhang parts of stator winding are copper busbars with insulation layer and air gap between each other. Thermal conductivity is low, and overhang conductors in the middle of the overhang layer are in hardest thermal condition.

Thermal calculation in «stator – rotor – stator overhangs – environment» system takes into consideration overhang position. Small air gap prevents air circulation, reducing heat convection

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between overhangs and stator core. The same situation we can see in air gap between stator and rotor. Without axial air flow, temperature of air between stator and rotor cores is high.

For thermal distribution calculation in stator winding and core, the following 3D mathematical model is given:

$$\frac{\partial T(r, x, t)}{\partial t} = \nabla \cdot \left(k \nabla T\right) + \frac{1}{c\gamma} Q(x, y, z, t)$$
(3)

Initial and boundary conditions are:

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$$\begin{cases} T(x, y, z, 0) = T_0 = T_C; \\ n \cdot (k \nabla T) = \alpha (T - T_C), \end{cases}$$
(4)

here: n – normal to the outer surface of computing area; c – specific heat capacity of conductors, core steel and insulation; γ – specific density of conductors, core steel and insulation; α – heat transfer coefficient; k – heat conductivity coefficient of conductors, core steel and insulation; Q(x, y, z, t) – internal heat sources distribution function.

Partial differential equation (3) describes conditions of copper conductors, laminated steel, wire and slot insulation. Anisotropy in stator core, defined by laminated stacks of steel, was considered in mathematical model.

3. Computer Simulation Results

Cross-section of conductors is $3,4 \times 1,74 = 5,9 \ mm^2$, total cross section of conductors in a stator slot – $34,5 \ mm^2$, and rotor slot – $40 \ mm^2$. Rms current is $60 \ A$, frequency – $50 \ Hz$.

For this current value and stator length 100 mm, thermal calculation has given the following results: in each stator conductor average power losses $\Delta P_1^S = 0.61 \div 0.988 \ W$, total power losses in six slot conductors $\Delta P_6^S = 4.963 \ W$, rotor conductor power losses $\Delta P_1^R = 2.191 \ W$. Instantaneous values of current and power losses in every slot differ from maximum values, and total power loss in stator conductors $\Delta P_{24}^S = 119.1 \ W$ and in rotor conductors $43.82 \ W$. Bulk power density in stator for this values of power losses $Q = 1.4 \cdot 10^6 \ W/m^3$.

The same calculations for overhang part show small influence of air gap width on bulk power density (table 1).

 Table 1.

 Δx, mm
 0,3
 1
 10

 Q, W/m³
 998000
 997000
 968500

Air gap between overhang parts and stator end-face has small impact on stator bulk power. Thus, this variable would have minimum value in case air gap exceeds 10 mm. For each 30 mm overhang conductor heat power $\Delta P_{1OV}^S = 0,177 W$, and for array of six conductors heat power is 1,062 W.

For stator end-face and the nearest overhang winding parts, air flow is parallel to stator end-face surface. Average air speed equals linear speed of the fan impeller outer parts:

$$v_0 = \omega r, \tag{5}$$

here: ω – rotor cycling speed, *r* – rotor radius.

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For 200 Hz source frequency and 4 pole-pairs number, rotation frequency equals 3000 rpm. Rotor radius is 0,044 m, so air speed reaches 13,86 m/s.

Reynolds number is defined by perimeter of average stator circle [21]:

$$\operatorname{Re} = \frac{v_0 l_m}{v} \tag{6}$$

Perimeter of stator circle:

$$l_m = 2\pi \left(r_{\max} + r_{\min} \right) / 2 = \pi \left(0.065 + 0.044 \right) = 0.342m \tag{7}$$

For air kinematic viscosity equals $v = 15.1 \cdot 10^{-6} m^2/s$, Reynolds number:

$$\operatorname{Re} = \frac{13,86 \cdot 0,342}{15,1 \cdot 10^{-6}} = 3,14 \cdot 10^{5}$$
(8)

Air flow mode is defined by Reynolds number. For flat surface streamlining, turbulence appears when Reynolds number exceeds $5 \cdot 10^5$. But in case of perturbance by complex form of overhang parts, unstable mode appears. Hence, we take into consideration turbulent air flow, and Nusselt number is [21]:

$$\overline{Nu} = 0.032 \,\mathrm{Re}^{0.8} = 0.032 \cdot \left(3.14 \cdot 10^5\right)^{0.8} = 799.27 \tag{9}$$

From another hand, Nusselt number is:

$$\overline{Nu} = \frac{\alpha \cdot l_m}{\lambda} \tag{10}$$

From this equation, convective heat transfer coefficient is:

$$\alpha = \frac{Nu \cdot \lambda}{l_m} = \frac{799,27 \cdot 0,0257}{0,342} = 60W / m^2 \circ C$$
(11)

here: λ – air heat conductivity, equals 0,0257 *W/m* °*C* for air temperature 20 °*C*.

Convective heat transfer coefficient varies from 5 $W/(m^2 \circ C)$ without air convection to 60 $W/(m^2 \circ C)$ with high intensity air flow. On the surfaces that are closed from the direct air flow transitional coefficient values are set. Every conductor part needs be considered in limit operation modes. Temperature distribution in stator for different overhang positions illustrated on fig. 3, 4.



Figure 3. Temperature distribution in stator for 60 *A* stator current and 2 *mm* air gap between overhang parts and stator steel.

Figure 4. Temperature distribution in stator for 60 *A* stator current and 15 *mm* air gap.

Heat transfer area on stator end-face decreases due to shielding by overhang parts, and stator steel temperature rises. At the same time, heat transfer in enclosed overhang parts decreases due to small air gap between stator and overhang parts.

Overhang conductors could be enclosed with common insulation for greater mechanic solidness and reliability. Thermal conditions for overhang parts are more difficult than for slot parts. This leads to temperature increasing, depicted on fig. 5. Temperature diagram illustrates asymmetrical thermal condition of different overhang conductors.



Figure 5. Temperature diagrams in overhang parts for: 1 – with common insulation; 2 – without common insulation.

Hence, to improve heat transfer in overhang parts they need common insulation without air gap between each other.

To increase air flow and heat transfer in stator end-faces, air gap between overhang parts and stator needs be increased. Temperature calculation for wide air gap is given below. Calculations are made for variety of heat transfer coefficients. Average results of temperature distribution in slot and overhang parts are given in table 2. IOP Conf. Series: Journal of Physics: Conf. Series 944 (2018) 012041 doi:10.1088/1742-6596/944/1/012041

Heat transfer coefficient, $W/(m^2 \circ C)$		Slot conductors temperature, $^{\circ}C$		Overhang conductors temperature, °C	
Stator end-face	Overhang	min	max	min	max
	parts				
30	29	107.5	109.5	108.3	109.1
30	35	98.8	100.6	99.1	100
30	39	86.8	88.9	86.8	87.7
60	43	73.5	75.8	72.8	73.55
60	29	90.3	92	89.8	90.3

Table 2. Temperature distribution	in stator	compact	winding.
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From this results we can see, that temperature gradient in slot and overhang parts becomes lower, as well as maximum temperature in machine. From the other hand, overhang deviation and total length increase.

4. Results Discussion

The given research work explains the possibility of significant reduction of induction machines dimensions. This is able due to original overhang parts construction. Innovative construction needs new methods of thermal calculation and machine design. Design of electric machine in static and dynamic modes should consider reduced heat transfer. Minimum temperature in windings and cores is the best criteria for construction optimization. Improved precision simulation should be held for heat transfer, thermal and electric conductivity determination, with the help of multiphysical models of electromagnetic, thermal fields and aerodynamics.

New construction of compact overhang parts allows to increase air gap between them and stator end-face. Big air gap reduces temperature gradient in stator winding. However, this solution negates positive effect of dimension reduction. It is necessary to conduct further researches of thermal reliability and cooling system optimization.

Conclusions

- 1. Proposed compact winding construction for induction machines allows to modify overhang deviation and rule thermal condition of machine.
- 2. To improve thermal conductivity of conductors, overhang parts are placed closely within common insulation.
- 3. To decrease temperature gradients within induction machine and improve heat transfer, air gap between overhang parts and stator should be increased.
- 4. Rely thermal condition allows to increase current and power of induction machines and startergenerators in static and dynamic modes.

References

- [1] Patzak A and Gerling D 2014 Design of an automotive 48V integrated starter-generator on the basis of an induction machine with concentrated windings *17th International Conference on Electrical Machines and Systems ICEMS* pp 2583–2589
- [2] Ishigami T, Tanaka Y and Homma H 2015 Motor stator with thick rectangular wire lap winding for HEVs *IEEE Transactions on Industry Applications* vol 51 issue 4 pp 2917–2923
- [3] Patzak A, Bachheibl F, Baumgardt A, Dajaku G, Moroz O and Gerling D 2016 ISCAD Electric High Performance Drive for Individual Mobility at Extra-Low Voltages SAE Int. J. Alt. Power vol 5 pp 148–156
- [4] Lysenko O A 2016 The research of axel-box 24-pole generators for communications systems of freight railway wagons 2016 Dynamics of Systems, Mechanisms and Machines (Dynamics)
- [5] Ismagilov F R, Vavilov V E, Karimov R D and Bekuzin V I 2015 High-speed-cal electromechanical energy converters with the possibility of integration of the aviation-engine

IOP Conf. Series: Journal of Physics: Conf. Series **944** (2018) 012041 doi:10.1088/1742-6596/944/1/012041

UAV Vestnik UGATU (scientific journal of Ufa State Aviation Technical University) vol 19 no 3 (69) pp 171–177

- [6] Dragomirov M S, Zhuravlyov S A and Zaitsev A M 2016 Analysis of cooling systems efficiency of traction induction motors and motor-generators *Vestnik ISEU* no 3 pp 39–43
- [7] Kobelev A S and Makarov L N 2016 Two electric vehicle traction motor design concepts *Proceedings of the 9th International (Russian) Conference on Automated Electric Drive (AED-2016)* pp 414–416
- [8] Grachev P Yu and Gorbachev E E RU Patent 2 526 835 Energy-efficient electrical machine 2014
- [9] Grachev P Yu, Gorbachev E E and Tabachinsky A S 2016 Power Converters with Compact Winding SCIGs for HEVs, Micro Hydroelectric Power Stations and Wind Turbines 2nd International Conference on Industrial Engineering, Applications and Manufacturing ICIEAM pp 1–5 DOI: 10.1109/ICIEAM.2016.7911521.
- [10] Bubnov A V2006 A comparative analysis of the ways to improve the dynamics of electric drive with phase synchronization *Russian Electro mechanics: Universities* News no 2 pp 24– 29.
- [11] Grachev P Yu, Strizhakova E V and Tabachinsky A S 2017 Starter-Generator Design and Analysis of Start/Stop Processes for HEVs *International Conference on Industrial Engineering*, *(ICIE-2017)*.
- [12] Grachev P Yu, Bazarov A A and Tabachinsky A S 2017 Compact Windings Design for Traction Induction Motors and SCIGs *International Conference on Industrial Engineering* (*ICIE-2017*).
- [13] Livadaru L, Munteanu A, Simion A and Cantemir C-G 2015 Design and finite element analysis of high-density torque induction motor for traction applications *9th International Symposium on Advanced Topics in Electrical Engineering, ATEE 2015* pp 211–214.
- [14] Tatevosyan A A 2017 The calculation of the magnetic field of the synchronous magnetoelectric generator *Dynamics of Systems, Mechanisms and Machines (Dynamics)*, DOI:10.1109/Dynamics.2016.7819095.
- [15] Sun J-L, Qiu C-W, Peng Y, Dong Z-K and Chang R-W 2016 Combined electromagnetic and thermal FEM modeling of heavy cylinder during induction heating process *Kang T'ieh/Iron and Steel* vol 51 issue 11 pp 93–100.
- [16] Kumar A, Marwaha S, Marwaha A and Kalsi N S 2010 Magnetic field analysis of induction motor for optimal cooling duct design *Simulation Modelling Practice and Theory*, Vol 18 Issue 2 pp 157–164
- [17] Iskierka S 1992 Finite element analysis of the performance of a ferromagnetic solid-rotor motor *Finite Elements in Analysis and Design* Vol 11 Issue 1 pp 1–8
- [18] Korkmaz S A and Kürüm H 2015 3-dimensional Analysis of Asynchronous Motor with Finite Element Method *Procedia Social and Behavioral Sciences* Vol 174 pp 4018-4025.
- [19] Wu J, Hu J, Chen A, Mei P, Zhou X and Chen Z 2016 Numerical analysis of temperature distribution of motor-refrigerant in a R32 rotary compressor *Applied Thermal Engineering* Vol 95 pp 365–373
- [20] Sarkar D and Naskar A K 2013 Computation of thermal condition in an induction motor during 4reactor starting *International Journal of Electrical Power & Energy Systems* vol 44 issue 1 pp 938–948
- [21] Mikheev M A and Mikheeva I M 1977 Osnovy teploperedachi.
- [22] Kim C and Lee K-S 2017 Numerical investigation of the air-gap flow heating phenomena in large-capacity induction motors *International Journal of Heat and Mass Transfer* vol 110 pp 746–752.
- [23] Kim C, Lee K-S and Yook S-J 2016 Effect of air-gap fans on cooling of windings in a largecapacity, high-speed induction motor *Applied Thermal Engineering* Vol 100 pp 658–667
- [24] Hosseini R, Ramezani M and Mazaheri M R 2009 Experimental study of turbulent forced convection in vertical eccentric annulus *Energy Conversion and Management* Vol 50 Issue 9 pp 2266–2274

- [25] Poncet S, Haddadi S and Viazz S 2011 Numerical modeling of fluid flow and heat transfer in a narrow Taylor–Couette–Poiseuille system *International Journal of Heat and Fluid Flow* Vol 32 Issue 1 pp 128–144
- [26] Boglietti A, Cavagnino A and Staton D 2007 Determination of critical parameters in electrical machine thermal models *42nd Annual Meeting of the IEEE. Industry-Applications-Society* (New Orleans, LA).