Research Article

Aicha Laidoudi*, Stéphane Duchesne, Fabrice Morganti, and Gabriel Velu

High-power density induction machines with increased windings temperature

<https://doi.org/10.1515/phys-2020-0131>

received April 10, 2020; accepted July 10, 2020

Abstract: The increase of the operating temperature of electrical machines is a major challenge in the context of the large-scale use of electricity in many industrial or individual applications such as mobility. Indeed, working at higher temperatures makes it possible to place electrical actuators in critical areas – such as aircraft engines, for example – and/or to significantly improve the power-to-weight ratio of the machine. For several applications (deep pumping, ventilation, etc.), the use of the induction machine is still preferred due to cost, simplicity and robustness essentially. The objective of this study is to estimate the possibilities of making a high-temperature squirrel cage induction machine. A significant increase in the operating temperature of a machine would indirectly allow us to envisage an increase in the current density in the active conductors and thus a significant improvement in the power-to-weight ratio. However, this is at the sacrifice of efficiency. The aim of this study is to evaluate this decrease in efficiency correlated with the increase in the temperature to find the best compromise according to the relevant applications. An analytic sizing model has been proposed for the prediction of losses, which will be coupled with a thermal model to predict the temperature in different parts of the machine. This study presents essential information on the influence of temperature on the parameters important for the performance of an induction machine.

Keywords: induction machine, high temperature, current density, power-to-weight ratio, machine efficiency

1 Introduction

Induction machines (IMs) are well-known components of electromechanical conversion chains mainly for their simplicity, robustness and affordability when used with a squirrel cage. The possibility of supplying them directly from the power grid makes them the preferred choice for ventilating or pumping applications, although in recent years they have more and more been coupled with variable speed drives to optimize their energy consumption. The environmental context has pushed the manufacturers to improve the efficiency of their machines to limit their environmental footprint as much as possible, which is how the IE2, 3 or 4 standards emerged.

However, there are more specific applications where the use of IMs remains privileged and for which the notion of efficiency may not be the most significant parameter. These applications will rather look for long service life and high availability of the machine. In this case, the machine environment can be strongly constrained by temperature, pressure, humidity or available volume, and therefore, it is necessary to find adequate solutions. The temperature increase remains the main challenge as it allows to face two problems.

First, some applications require electric motors that can operate in hot environments, such as in future aircraft turbines designed using open rotor [1,2] technology or in closed environments with limited or no cooling, such as near the hot flow of an aircraft engine. Other industrial applications such as hot air ventilation in case of fire are also concerned.

Second, increasing the current density in the conductors of a rotating electrical machine is equivalent to increasing its power-to-weight ratio, which is crucial in terms of space and weight for on-board applications [3,4]. The marine propulsion system is currently evolving toward all-electric propulsion and let's take this

* **Corresponding author: Aicha Laidoudi**, Univ. Artois, UR 4025, Laboratoire Systèmes Electrotechniques et Environnement (LSEE), F-62400, Béthune, France, e-mail: aicha.laidoudi@univ-artois.fr
Stéphane Duchesne: Univ. Artois, UR 4025, Laboratoire Systèmes Electrotechniques et Environnement (LSEE), F-62400, Béthune, France, e-mail: stephane.duchesne@univ-artois.fr
Fabrice Morganti: Univ. Artois, UR 4025, Laboratoire Systèmes Electrotechniques et Environnement (LSEE), F-62400, Béthune, France, e-mail: fabrice.morganti@univ-artois.fr
Gabriel Velu: Univ. Artois, UR 4025, Laboratoire Systèmes Electrotechniques et Environnement (LSEE), F-62400, Béthune, France, e-mail: gabriel.velu@univ-artois.fr

opportunity to list the advantages of pod propulsion. For this type of propulsion, to achieve acceptable energy efficiency, it is necessary to work on the shape of the bulb and to use high power density electric machinery accordingly.

The current densities chosen by designers of rotating machines rarely exceed 6 A mm^{-2} , except for machines with advanced cooling systems such as water-cooled actuators or turbo generators.

Increasing current densities causes heating that the organic insulating materials used in the majority of cases cannot withstand.

The use of more compact actuators not only has an economic impact in terms of manufacture and use but also has an environmental impact. Therefore, the advantage of being able to increase the operating temperature of machines is clearly visible. Many difficulties arise at different levels. Indeed, it is not only the problem of design that must be taken into account but also the type of machine, the entire machine, that must be reconsidered: the constituent materials must be identified and characterized, so as to redefine the rules of evolution as a function of temperature.

This study involves studying the possibility of machine to operate at high temperatures without taking into account the insulation systems and studying the influence of temperature on the power-to-weight ratio and in the necessary parameters that define its performance.

This article could be a great help in selecting the better candidate, high-temperature electrical machines.

First, a brief state of the art will help to clarify the context of high-temperature machines that is not very common. This provides the authors the opportunity to clearly define their objectives in this study.

The rest of this article is organized as follows:

Section 3 explains how we manage to estimate the possibilities of building a high-temperature IM based on variation of the current density. Two model, thermal and analytic modeling are proposed. Simulation results will be discussed and analyzed in a comprehensive manner in Section 4.

Section 5 presents conclusion that proposes different solutions and phenomena that should be taken into consideration.

2 State of the art and philosophy

Over the last few decades, several prototypes of high-temperature machines have been studied. Each of them was most often based on a classical design using materials suitable for high-temperature applications.

A prototype high-temperature machine was built by General Electric researchers in Schenectady, New York. It is a small electric motor that operates at temperatures up to 725°C , showing the possibilities of a new high-temperature electrical conductor: a silver–palladium wire (50–50%) with a nickel plating. The conductor was developed by *C.S.Tedmon*. This wire was manufactured by inserting a silver–palladium rod into a nickel tube. Some interdiffusion of nickel and silver–palladium can occur at the boundary with the (nickel) plating [5,6].

A model of isolated inorganic coils capable of operating at 200°C has been developed by the author of the quote. These coils were mounted on a prototype permanent magnet synchronous machine that was used to solve the problem of high-temperature insulation. With the best magnets available on the market, it is difficult to exceed an ambient temperature of about 200°C [8,9], and the only magnets capable of operating up to 500°C are metallic magnets, which have a very low coercive field, so they cannot be used in the machine. Samarium and cobalt can be used in the machine and can operate in a temperature range of 300°C – 200°C , but the coercive field falls at high temperatures and it must be accepted. In addition, the rotor design must take into account the high electrical conductivity of metallic magnets. The metal magnets must be fragmented to limit losses due to harmonics in the flux density [11].

For exceeding the maximum temperature imposed by the magnets, synchronous reluctance machines can be a good choice of the machine type. The stator is similar to the one proposed in ref. [7], but the rotor is only made of soft magnetic materials. This machine is magnetized by the stator currents. The author of refs. [10,12,13] proposed a winding structure that allows the machine to be supplied with the usual voltages produced by PWM inverters despite the low electrical performance of the ceramic-coated wire. The method of construction of these coils is developed in the paper study [11].

However, the IM is the most widely used in all industrial fields thanks to its simplicity of manufacture, cost and concept of use. Its good efficiency and excellent reliability mean that IMs powered directly from the mains make up the majority of industrial applications.

In this context, the evaluation of the temperature rise potential of IMs is an interesting issue for many manufacturers, whether for very specific application or cost reasons, even if at first it may not be the most suitable machine for high-temperature operation.

Our study focuses on squirrel-cage induction motors by assessing their thermal and electrical potentials,

means having an IM that has a high power density and can operate at high temperatures.

Dielectric materials, fundamental components of the electrical insulation system of motors, see their operating temperature increase regularly. In that sense, we intend to establish some numerical quantities to evaluate the real possibility of this type of machine at high temperature, and in other words, we need to know the impact of the temperature increase on the efficiency of the machine.

3 Approach

This study deals with a three-phase IM where the current density, the main input variable, is increased. This choice is not unexpected since the current density is a particularly relevant parameter to increase the power-to-weight ratio of the machine. To do this, the characteristics of the materials are fixed, and the modifications will be applied to the stator first and then to the stator and the rotor.

In this study, two main steps were established. Figure 1 shows the steps of the approach followed.

Our approach consists in realizing an analytic design model to identify for each current density value, geometrical parameters such as the diameters of the machine components (rotor, stator and shaft) and electrical parameters such as wire diameter, losses and resistance. For the first iteration, a current density value was imposed on a usual value.

By using the geometrical parameters obtained from the analytic design model, a 2D finite element simulation with the FEMM software was chosen to provide a relevant support for the calculation of the machine efficiency.

A thermal model estimates the temperature in the different parts of the machine, which will be taken into account again during the analytic sizing model.

The calculation of the loop is done using Matlab/Simulink.

In the first part of this study, the inner diameter is constant, and only the current density evolves. Then, in the second part, the inner diameter becomes variable by keeping the ratio $D_a^2 \cdot L$ constant (D_a is the inner diameter and L the iron length). This makes it possible to define a set of preoptimized parameters to obtain relevant values of efficiency or the power-to-weight ratio.

3.1 Analytic sizing model

The design of electrical machines is based on simple formulas that aim to determine, on the one hand, the general geometry of the machine and its active parts (windings, magnets) and, on the other hand, to determine the magnetic and electrical parameters such as resistance, inductance and losses.

There are several design methods, and we chose to use the method developed by Bouchard [14,15]. This is based on the engine power and speed. Thus, the geometrical dimensions of the air gap are a function of the coefficients and variations of the motor parameters. With this method, the inner diameter remains unchanged.

However, we have used analytic formulas and hypotheses, but we needed some data that come from the previous experiences of the builders and the literature [16,17]. These values remain flexible and are accessible at the final application level for editing.

The estimated losses [18] will be used as sources for the next step.

Figure 1: Steps used in our approach.

3.2 Thermal model

The thermal resistances are calculated for the basic geometries that are cylinder and parallelepiped [19–22]. Figure 2 shows the two geometries used in the computation of the thermal resistances.

$$R_{\text{th conduction}} [\text{K W}^{-1}] = \begin{cases} \frac{1}{2 \cdot \pi \cdot \lambda \cdot L} \cdot \log \frac{R_2}{R_1} & \text{if cylinder;} \\ \frac{H}{\lambda \cdot e \cdot L} & \text{if parallelepiped.} \end{cases}$$

Figure 2: Parallelepiped (left) and cylinder (right) model.

$$R_{\text{th convection}} [\text{K W}^{-1}] = \frac{1}{h_{\text{conv}} \cdot S}.$$

where R_1 and R_2 are the inner and outer diameter, respectively (Figure 2).

λ is the conduction coefficient, h_{conv} is the convection coefficient and S is the section crossed by the heat flux. Most of the elementary parts of the IM are characterized by a material; therefore, a single thermal coefficient will be considered, except the winding of the machine (notch) because this zone is made up of enamelled copper with a fill factor α_{win} and air. However, obtaining an equivalent thermal conductivity is quite complex. As a solution, the author of ref. [21] suggests the following equation to evaluate it:

$$\lambda_w [\text{Wm}^{-1} \text{K}^{-1}] = \frac{\lambda_{\text{cu}} \cdot \lambda_{\text{air}}}{\lambda_{\text{air}} \cdot \sqrt{\alpha_{\text{win}}} + (1 - \sqrt{\alpha_{\text{win}}}) \cdot \lambda_{\text{cu}}}.$$

The simplified thermal model shown in Figure 3 is applied to the IM geometry.

The resistances R_1 , R_2 , R_3 , R_4 and R_5 characterize the main heat exchanges. A small part of the rotor losses flow outside the machine through the shaft, and this transfer corresponds to the thermal resistance R_5 . The heat flux to the atmosphere, symbolized by R_3 , corresponds to the cooling fan that blows cold air on the outer surface of the engine casing and its fins.

Figure 3: Motor steady-state thermal model.

Table 1: Thermal resistance values for 11 kW induction machine

Thermal resistances	R_1	R_2	R_3	R_4	R_5
Value (K W^{-1})	0.5	0.071	0.078	0.12	41.6

This model also takes into account the internal couplings of the machine; the power flow through the air-gap is modeled by R_4 , but the turbulence in the openings of the stator slots also creates a thermal coupling R_2 between the rotor and the windings.

r , w , s and o correspond to the rotor, winding, stator and ambient temperatures, respectively. The heat sources P_r , P_w and P_s are the losses in the rotor, the windings and the stator core, respectively.

Some hypotheses are made:

- The heat flux of the machine is uniform.
- Heat transfer is done by conduction and convection.
- The model does not take into account the axial airflow in the air gap or the complex interactions that exist in the end zones (end-winding).

This model can estimate the steady-state temperature reached in different parts of a machine (rotor, windings and stator). It has been calibrated using experimental tests.

Table 1 presents the thermal resistance values represented in the thermal model (Figure 3) for the 11 kW IM.

3.3 Validation of thermal model

Two experimental tests are established on an 11 kW IM (Figure 4) to validate our thermal model shown in Figure 3.

Table 2 represents geometrical and electrical parameters of machine:

1. No load test where the rotor copper losses are negligible, and the results are illustrated in Figure 5.
2. A locked rotor test for 23 A where the mechanical losses are zero, and the results are shown in Figure 6.

The recovery of temperatures is done using thermocouples. In the steady state, the simulation and experimental results are summarized in Table 3.

For the no load test, according to Figure 5 and Table 4, in the steady state, the temperature in the coil that the thermocouple provides is 79°C . The values found in simulation in this case is equal to 74°C , and it can be seen that the two values are close with an error of 4%.

Figure 4: Three-phase IM of 11 kW.

Table 2: Dimensions and electrical quantities of 11 kW induction machine

Quantity	Value
Power (kW)	11
Number of pole	2
Frequency (Hz)	50
Voltage (V)	400
External diameter (mm)	253.8
Inner diameter (mm)	123.6
Shaft diameter (mm)	41.41
Air gap (mm)	0.55
Number of stator slot	36
Number of rotor slot	28
Iron length (mm)	116.49

Table 3: Simulation and experimental results of 11 kW induction machine

	Temperature results	Stator (°C)	Rotor (°C)
No load	Simulation	74	—
	Experimental	79	—
Locked rotor	Simulation	223	319
	Experimental	232	324

For the short circuit test, according to Figure 6, in the steady state, the temperature values for the windings and the rotor are 232°C and 324°C, respectively.

The simulation gives temperatures of 223°C and 319°C for the windings and the rotor, respectively. In fact the difference between measurement and simulation is low, hence the validity of our thermal model.

Figure 5: Winding temperature for the no load test of machine.

Figure 6: Experimental results for the short circuit test of machine.

4 Simulation results

The results presented in this article concern:

- The variation of temperature in different location of machine.
- The influence of the current density on the efficiency.
- The influence of the current density on the power-to-weight ratio.
- The influence of the current density on the torque.

The aforementioned are for a fixed inner diameter. We vary the latter, and we study its impact on

- the efficiency,
- power-to-weight ratio and
- the torque.

The computations are made for 11 kW IM at 50 Hz for increasing the current density from 0 to 30 A mm⁻² with a small step of 1 A mm⁻².

Using Bouchard's analytic design modeling method, the inner diameter is fixed.

Figure 7: Evolution of temperature in different parts of the machine.

4.1 Fixed inner diameter

The inner temperatures of the machine obtained using the thermal model are plotted in Figure 7.

Figure 8 shows the evolution of the efficiency with the current density.

It appears that the rotor, stator and windings temperature curves increase almost linearly with the increase of the current density.

It can be seen also that the windings temperature curve is higher than the temperature in the other locations, and it confirms that the temperature class of the windings is the main limit of the high-temperature machines.

According to Figure 8, it may be observed that the efficiency decreases linearly with the increase of the current density. Typical evolution of the power-to-weight ratio with the current density is presented in Figure 9.

According to Figures 7–9, the operating point of our 11 kW machine are current density of 5 A mm^{-2} , efficiency

Figure 8: Evolution of the efficiency according to the current density.

Figure 9: Evolution of the power-to-weight ratio according to current density.

of 0.88 and a power-to-weight ratio of 380 W kg^{-1} . The machine and its 2D design in FEMM software are illustrated in Figure 10.

The number of conductors decreases gradually with increases of the current density. We perceive here the interest of being able to work at high temperatures, true also for the size of the notch thanks to the increase of the current density. Under these conditions, the tooth width and the height are reduced favorably impacting the outside diameter as illustrated in Figure 10. These value can decrease to a permissible value that depends mainly on the saturation of the stator teeth.

To gain in weight, the current density is increased, for example, for a current density of 22 A mm^{-2} , the power-to-weight ratio is 500 W kg^{-1} and the temperature is 300°C . Accordingly, the machine efficiency decreases from 0.9 to 0.78 (10%). Therefore, the increase of the temperature makes it possible to reduce the dimensions of the machine at the price of a less good efficiency.

Figure 10: 2D design of a 11 kW induction machine using FEMM software [23].

Increase in the power shows its influence on the inner diameter, temperature and power-to-weight ratio.

Figures 11 and 12 show variation of the temperature and the power-to-weight ratio for 30 kW IM.

According to Figure 12, to have a power-to-weight ratio of 500 W kg^{-1} , the current density should be around 10 A mm^{-2} .

In fact, the increase of the power, the inner diameter and the external diameter vary inversely according to the length of the machine.

Figure 13 represents the variation of efficiency according to the current density for 30 kW IM.

It can be seen that at 10 A mm^{-2} , the efficiency is around 0.87. In this case, the temperature has reached 410°C (Figure 11), thus making the temperature gain of the IM limited.

Figure 14 shows the influence of power on the inner and external diameter.

Figure 15 shows the torque-slip characteristic of 11 kW machine for different current densities.

In this step, using the thermal model, we estimated the temperature for each current density and recomputed at operating temperature the electrical parameters

Figure 13: Efficiency of 30 kW induction machine.

Figure 11: Temperature for 30 kW induction machine.

Figure 12: Power-to-weight ratio for 30 kW induction machine.

Figure 14: 2D design using FEMM software for two different power values.

Figure 15: Torque-slip characteristic for different current density values.

such as resistance, reactance using analytic model design adapted to high temperature.

On the basis of these parameters and for a fixed inner diameter, we plotted the torque-slip characteristic. For the experienced 11 kW machine, the characteristic torque-slip is shown in black, the maximal torque is 64 N m and the maximal slip corresponding to this maximal torque is around 0.3.

It can clearly notice that for a fixed load (a fixed the torque), the maximum slip increases with the increase in the current density, and if we fix the slip (the speed), the torque supplied decreases. This is depicted in Figure 15.

The increase in the temperature shows a characteristic that resembles that of the overload of the machine, and this is due to the increase in the maximal slip (Slip_m), which is a function of the rotor resistance as shown in the following equation:

$$\text{Slip}_m(T) = \frac{R'_r}{X_f},$$

where R_r is the rotor resistance, which increases with the temperature; X_f is the rotor reactance; and T is the operating temperature.

Bouchard's method focuses on a constant D^2L ratio.

To have a higher power-to-weight ratio than the one mentioned in the previous section, the reduction of the inner diameter can be a solution by using another sizing method that is based on other parameters to be imposed such as the linear load. By increasing this one, the inner diameter decreases according to this formula:

$$A_c = \frac{N_c m I_s}{D_a \pi},$$

where A_c is the linear load (A m^{-1}), m is the phase number, I_s is the current phase (A) and D_a is the inner diameter (m).

4.2 Variable inner diameter

The below simulation results are for an inner diameter D_a and the current density (J) variable, while always keeping a constant $D_a^2 \cdot L$ ratio.

When the current density is fixed at 5 A mm^{-2} , i.e.: for a given temperature. Figure 16 shows the torque-slip characteristic for different values of inner diameter.

According to Figure 16, it can be seen that for a fixed speed, if the inner diameter increase, torque supplied increases.

Figure 16: Torque-slip characteristic for 5 A mm^{-2} and different inner diameter values.

Figure 17: Variation of the efficiency according to the inner diameter for different current density values.

As the torque is a force linked to a circular movement, it is made up of two values: the force F and the radius of the shaft linked to the load R as shown in the following equation:

$$\Gamma = F \cdot R_{\text{shaft}}.$$

For the tested machine (blue curve) with a current density of 5 A mm^{-2} , the maximal slip is 0.3.

From the equation of the torque, it can be deduced that, for a fixed speed, the increase in torque is due to the diameter of the shaft which decrease as the inner diameter decreases.

Figure 17 summarizes the evolution of efficiency according to the inner diameter for different values of the current density.

Figure 18: Variation of the efficiency according to the power-to-weight ratio and the current density.

According to Figure 17, for the same current density value, it can be observed that, for small bore diameter values, the efficiency increases with the increase of the inner diameter up to a value where the efficiency becomes maximum. This represents the optimum operating point.

Hence, the more we increase the inner diameter, the efficiency decreases until it reaches very low values.

Now, the inner diameter and the current density are variable, and the goal is to determine the optimal points where the efficiency is better and the power-to-weight ratio is the highest. Figure 18 shows the 3D variation of efficiency with the power-to-weight ratio and current density.

It can be concluded from Figure 18 that for each value of current density, there is an optimal value of efficiency. This is obtained for values of inner diameter, iron length and a precise load (slip).

The black line shown in Figure 18 represents the Pareto solutions. The blue arrow and frame show the optimum and its coordinates. This represents the best compromise for our application.

Table 3 summarizes a comparison between a machine optimal quantities with two different current density values 5 and 20 A mm⁻².

By increasing the current density from 5 to 20 A mm⁻², there is an increase of 24% in the power-to-weight ratio corresponding to a decrease of 18% in efficiency. Furthermore, the machine will have an inner diameter of 1.2 times less, a length of 1.3 times longer and 2 times the temperature or even. This is the case of torpedo engines for submarines, which had colossal current densities for a tiny lifetime.

Table 4: Pareto graph synthesis

Current density (A mm ⁻²)	5	20
Efficiency (%)	88	73
Power-to-weight ratio (W kg ⁻¹)	350	466
Inner diameter (mm)	88.29	77.25
Iron length (mm)	228	298
Operating temperature (°C)	135	260
Stator losses (W)	540	2,830
Rotor losses (W)	333.5	491
Corresponding slip (%)	2.7	4.1
Iron losses (W)	187	139

Indeed, working at high temperature and changing inner diameter keeping its inner volume constant make it possible to increase the power-to-weight ratio but a decrease in efficiency in case of price.

So, what we gain in the power-to-weight ratio, we pay for efficiency.

Concerning the losses, it can be observed that copper losses are the most dominant losses. This is due to the load (slip), which is low in this case (from 2.7% to 4%). If we add more load (we go up in slip), the rotor losses will increase and approach more to the transmitted power due to the high rotor current in the bars. In fact, the temperature that limits the operation of the machine is that of the rotor.

5 Conclusion and prospect

The design of a high temperature electric machine is still difficult to perform because of the many compromises and the significant decrease in the performance of materials that evolve significantly with the increase in temperature.

This study has highlighted several important things related to the sizing of a high-temperature IM, where:

- The limit gain in temperature is concluded.
- It presents the trends of the parameters as a function of temperature and their influence on the performance of high-temperature IMs. These include key parameters that determine the design of electrical IMs at high temperatures.
- Changing the inner diameter and keeping a constant inner volume allows: gain in power-to-weight ratio but loss in efficiency in case of price.

To have a good design and refine the results of high-temperature IM, we should take into account the influence of temperature on the other parameters such as:

- The permeability for inductions greater than 0.6 T increases with the increase of the temperature.
- The coercive field to magnetize the circuit decreases with the increase of the temperature;
- The saturation induction shows a constant weakening with the increasing temperature.

The current technological limit for machines is clearly the insulation of electrical conductors. Then, for working in median ranges temperature and maintaining a good efficiency, applying the sol-gel process to the enameling layer of a copper wire appears as a very attractive solution. It is not the case for squirrel cage IMs. It can be effective only if the machine is designed to be used for working at low loads, but for large loads, the rotor heating limits its operation.

Using bars that resist the high temperature or increase their cross section can be a solution.

References

- [1] Iosif V, Roger D, Duchesne S, Velu G. 2014. Experimental characterization of the maximum turn-to-turn voltage for inorganic high temperature motor. In 2014 IEEE Electrical Insulation Conference (EIC). Philadelphia, PA, USA: IEEE. p. 69–73. doi: 10.1109/EIC.2014.6869349
- [2] Assaad B. Contribution à la prise en compte des aspects thermiques des machines électriques dans un environnement mécanique. PhD thesis. Compiègne; 2015.
- [3] Cozonac D. Conception d'une machine asynchrone haute température. PhD thesis. Artois University; 2015.
- [4] Lateb R. Modélisation des machines asynchrones et synchrones à aimants permanents avec prise en compte des harmoniques d'espaces et de temps, Application à la propulsion marine par POD. 2006. Thèse de doctorat. Thèse de Doctorat de L'INPL.
- [5] A high temperature electric motor use of nickel-clad silver palladium. *Platin Met Rev.* 1971;15(3):100–1.
- [6] Roopnarine N. Motor for high temperature applications. U.S. Patent No 8,581,452, 12 Nov. 2013.
- [7] Iosif V, Takorabet N, Roger D, Duchesne S, Meibody-Tabar F. Conception d'un prototype de machine ultra-haute température (500°C). *Electrical Engineering Symposium (SGE)*. Jun 2016.
- [8] Lefik M, Komeza K, Juszczak EN, Roger D, Napieralski P, Takorabet N, et al. High temperature machines: topologies and preliminary design. *Open Phys.* 2019;17(1):657–69. doi: 10.1515/phys-2019-0068
- [9] Liu JF, Walmer MH. Thermal stability and performance data for SmCo 2: 17 high-temperature magnets on PPM focusing structures. *IEEE Trans Electr Devices.* 2005;52(5):899–902. doi: 10.1109/TED.2005.845868
- [10] Komeza K, Lefik M, Juszczak EN, Roger D, Takorabet N, Meibody-Tabar F. Analysis of the impact of the design of HT machines on the cogging torque and losses in permanent magnets. 2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES). IEEE; 2016. p. 1–6.
- [11] Lefik M, Komeza K, Juszczak EN, Roger D, Napieralski P. Comparison of the reluctance laminated and solid rotor synchronous machine operating at high temperatures. *COMPEL-Int J Comput Math Electr Electron Eng.* 2019;38(4):1111–9.
- [12] Elmadah H, Roger D, Takorabet N. Design of inorganic coils for high temperature electrical machines. *Open Phys.* 2019;17(1):698–708. doi: 10.1515/phys-2019-0072
- [13] Komeza K, Lefik M, Roger D, Juszczak EN, Elmadah H, Napieralski P, et al. High temperature permanent magnet synchronous machine analysis of thermal field. *Open Phys.* 2019;17(1):631–42. doi: 10.1515/phys-2019-0065
- [14] Boldea I, Nasar N. *The Induction Machines Design Handbook*, Second Edition, ser. Electric Power Engineering Series. Taylor & Francis; 2009.
- [15] Soong WL. Sizing of electrical machines. *Power Eng Brief Note Ser.* 2008;9:17–8.
- [16] Pyrhonen J, Jokinen T, Hrabovcova V. *Design of rotating electrical machines*. John Wiley & Sons; 2013.
- [17] Mellor, PH, Roberts, D, Turner, DR. Lumped parameter thermal model for electrical machines of TEFC design. *IEE Proceedings B (Electric Power Applications)*. IET Digital Library; 1991. p. 205–18. doi: 10.1049/ip-b.1991.0025
- [18] Jimoh AA, Findlay RD, Poloujadoff M. Stray losses in induction machines: part I, definition, origin and measurement. *IEEE Trans Power Appar Syst.* 1985;6:1500–5. doi: 10.1109/TPAS.1985.319165
- [19] Bousbaine A, McCormick M, Low WF. *In-situ* determination of thermal coefficients for electrical machines. *IEEE Trans Energy Convers.* 1995;10(3):385–91. doi: 10.1109/60.464858
- [20] Staton D, Popescu M, Cossar C, McGilp M, Omori S, Kurimoto T. Analytical thermal models for small induction motors. 2008 18th International Conference on Electrical Machines. IEEE; 2008. p. 1–6. doi: 10.1109/ICELMACH.2008.4800139
- [21] Kylander G. Thermal modelling of small cage induction motors. Chalmers University of Technology; 1995.
- [22] Daffeur N. Modélisation thermique par éléments finis d'un moteur asynchrone à cage. PhD thesis. Université Mouloud Mammeri; 2010.
- [23] Meeker D. Finite Element Method Magnetics: OctaveFEMM. 2010.