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Comparison of the Reluctance and Permanent Magnet Synchronous Machine operating at High Temperatures

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The paper describes 3D analysis of the thermal field in permanent magnet synchronous machine and reluctance synchronous machine able to work at high internal temperature (HT° machine). 3D coupled fluid-thermal model of projected machine is created to obtain the distribution of thermal field and air flow and to calculate the average temperature of the most sensitive parts such as coils and permanent magnets. The influence of the surface state of the machine housing on its heating is examined. The points of the highest temperature inside analyzed machine are localized too. The comparison of thermal properties and the possibility of working at high temperatures for both kinds of machines has been carried out.

Index Terms— Fluid dynamics, Permanent magnet machines, Synchro-reluctant machine, High Temperature, Thermal analysis.

I. INTRODUCTION

THE HT° ELECTRIC MACHINES are designed for special purposes. They are used in environments where the ambient temperature is much higher than typical ones. Of course, this also causes an increase the temperature inside the motor housing. For example, the Permanent Magnet Synchronous Machine (PMSM) designed for working in the vicinity of the aircraft turbines, where the ambient temperature is about 200°C, will work with an internal temperature estimated to 450-500°C at the hottest point. In order to work continuously at such internal temperatures it is necessary to use inorganic Electrical Insulation Systems (EIS) and to adapt the machine design to this inorganic technology [1-4]. With this topology, two main options are possible: a synchronous permanent magnet machine, or a reluctance synchronous machines which produces torque from variations of the reluctance of the magnetic circuit [5-7]. In the case of a machine with permanent magnets special SmCo permanent magnets must be used and these magnets have a relatively high electrical conductivity in comparison to the classical ones. During the design process of these HT° PMSM a particular attention must be paid to thermal strength of the winding insulation and the operating temperature of permanent magnets. The HT° motor, made with rigid inorganic coils, requires a specific design of the stator with rectangular teeth and opened slots. The slotting effect is much higher than for a classical machine; the only available magnets have a higher electric conductivity, the machine design must take these effects into consideration adding magnetic wedges between the stator teeth and segmenting the magnets. Thus, the design calculations of those electromechanical transducers require specific electromagnetic and thermal analyzes, which allow calculating additionally the thermal effects of power losses.

The paper describes the thermal analysis of HT° PMSM and HT° Synchronous Reluctance Machine (SRM) operating at high ambient temperatures using 3D field calculations. The machine is run at the rated speed of 5650 rpm. To analyze this phenomenon the 3D coupled thermal-fluid (CFD) model is used. The distribution of the temperature field and average temperature of the windings and permanent magnets (in the case of PMSM) are calculated. In addition, points with the highest value of the temperature (hot points) are localized. The impact of color and surface condition of the motor housing on the temperature distribution, the influence of the type of the material used for magnetic wedges, conductivity and segmentation of the permanent magnets on the power losses in the magnets is examined. This allowed the optimal way to choose the material and design to develop a prototype of the machine.

II. CHOICE OF TOPOLOGY OF HT° MACHINES.

As part of this project consists in studying the feasibility of such a machine with its power supply that can work durably in a warm environment. The choice of structure of the machine can be guided by different aspects mainly related to the materials used to the manufacture of active parts.

In general, it is recommended to avoid machines with brushes. The rotor in this case is powered via a sliding contact system. Indeed, two major difficulties are inherent in this type of machines. The first being the wear and the oxidation of the parts in contact which risks being accentuated by the effect of heat and thermal cycles. The second concerns the presence of a winding at rotor made of rigid inorganic materials that would be subjected to mechanical stress and vibration in addition to the constraints related to the temperature. The cage induction machine is rejected because of the need to use distributed windings that require

some flexibility of the coils. Of course, it is still possible to use rigid coils but at the expense of compactness. The induction machine is still a track which can be explored in the future.

Aside from asynchronous machines, standard brushless machines that can be tested are permanent magnet machines or variable reluctance machines. The choice is made on a synchronous machine with permanent magnets and / or a synchronous reluctance machine (SRM) so that one same dental winding stator can be used with two different rotor structures in architecture and materials. This makes it possible to have an alternative solution in the case where the rotor with permanent magnets has temperature resistance problems beyond certain limits.

In synchronous magnet machines, two magnet mounting technologies are possible: surface mounting and embedded inside the rotor. The first option is the easiest to achieve but it place the magnets close to the stator coils, therefore at a high temperature. The second solution places the magnets inside the rotor core; the flux is concentrated towards the air gap by soft magnetic parts. The magnet temperature is lower. In both cases, the design of the rotor must provide for a direct evacuation of the heat created in the magnets by the eddy currents. In the case of the synchronous machine with wound rotor we will find a stator winding and rotor winding with inorganic insulated wire. Joule losses will be accentuated in high temperature. The sliding connection system that connects the rotor coils to the circuit outside is quite tricky to achieve at conventional temperatures. It is not reasonable to consider it in HT. The only reasonable structure is therefore the Permanent Magnet Synchronous Machine (MSAP) which uses special SmCo alloys with a preference for the embedded magnet machine.

Synchronous reluctance machines have very different structures. Our machine uses the same basic physical principle as all the others: the torque results by the variations of the magnetic energy stored in the motor at a given instant. In a conventional synchronous machine, the distributed windings are traversed by a balanced three-phase current system. The stator creates a rotating magneto motive force (mmf) with a sinusoidal spatial distribution. Induction in the air gap results from this mmf. The mmf brought by the rotor (magnets or direct current in the excitation coils) and the geometry of the gap. When the rotor has salient poles, the natural spatial variations of the induction create a reluctant torque when the rotor mmf is zero. This effect can be amplified by varying the amplitude of the stator mmf, the geometry of the rotor and the anisotropy of the magnetic materials of the rotor. Therefore, the SRM is a special case of salient pole synchronous machine; the magnetic energy in the gap is only provided by stator currents; a part of the reactive power is used for magnetizing the machine. With this structure, the magnets are no longer useful, which is very interesting because it eliminates this technological lock. However, this topology needs larger stator mmf and a reduced air-gap. Thermal expansions can create mechanical problems. On the other hand, this topology needs to use a larger number of turns for the stator windings which increases the difficulty of designing the coils. This structure can operate at higher temperatures than the PMSM but with a lower power factor and lower energy efficiency. This type of machine, however, remains the only solution for the highest temperatures.

The figure 1 gives an idea of the two topologies envisaged for the electric motor. The study is first focused on the permanent magnet machine with the two variants of magnet placed on the surface or magnets inserted in the rotors.

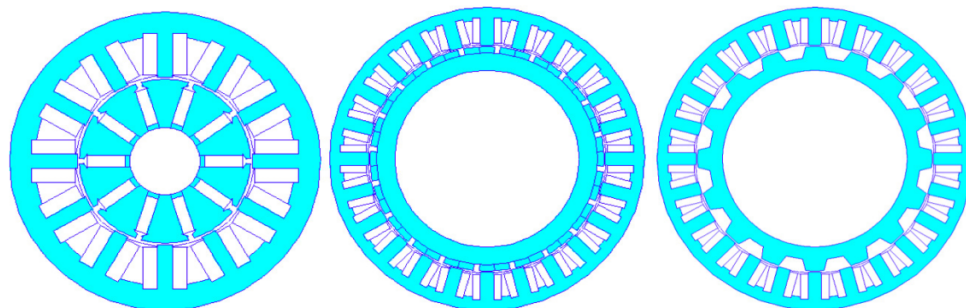


Fig.1. Different topologies of the machines (a) PMSM with embedded magnets, (b) PMSM with surface magnets, (c) VRM

These machines have the advantage of following similar rules as to the choice of the number of stator slots and number of poles so that a stator of a PMSM can be used for variable reluctance machine provided that the number of turns or the voltage level is adapted. The most important criterion that led to this choice is the possibility of using prefabricated rigid coils insulated by inorganic materials. The shape of the stator slots must be adapted to these rigid coils and their insertion. For the magnet machine placed on the surface, it is sufficient to adapt the height of the magnets and their arrangement so that they produce the necessary flux. Particular attention is paid to losses in magnets due to the magnetic reaction of the armature or to the effect of the stator teeth. A segmentation of each magnet in 4 pieces (2 in the azimuthal direction and 2 in the axial direction) is sufficient to reduce these losses without increase the complexity of manufacturing and assembly. Figure 2 gives some elements on the design of the magnet rotor placed on the surface.

Regarding the inserted magnet rotor (flux concentration), we kept the same number of poles so as to keep the same stator winding. The peculiarity of this topology lies in the sizing or design of flux barriers. Indeed, it is essential to limit the flow of rotor leakage to take full advantage of the flux of magnets. The chosen topology is described in Figure 3. The slots provided for inserting the magnets into the magnetic circuit of the rotor is open on the lower side (shaft side) so that the flux does not loop

back by the non-magnetic rotor. The upper side of these slots (air gap side) is closed by a band narrow to form a flux barrier by saturating itself. The thickness of this band is dimensioned from so that it holds mechanically but is very magnetically saturated. In the same way as for magnets placed on the surface, the inserted magnets are also subdivided into 4 pieces to limit the losses and heating. Naturally, the topology with inserted magnets better protects magnets that are not directly exposed to the armature reaction field or to the heat flux that may come from the stator following an over-heating.

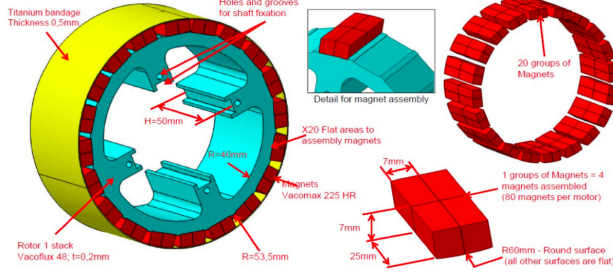


Fig.2. Soft magnetic circuit with magnets on the surface.

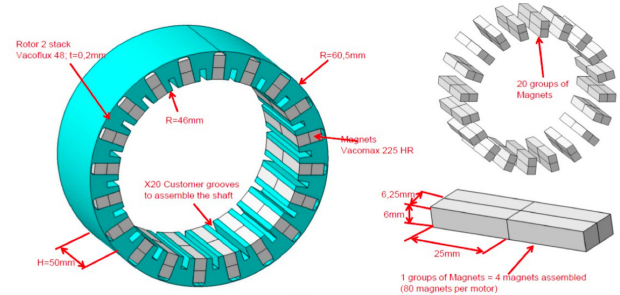


Fig.3. Soft magnetic circuit with embedded magnets.

III. MATHEMATICAL MODEL

CFD analysis model it is a 3D thermo-fluid coupled mathematical model, which is based on Computational Fluid Dynamics method. This mathematical model uses Navier-Stokes equations which in case of the turbulent fluid flow take a form of Reynolds-averaged Navier–Stokes equations (RANS equations). RANS equations for the steady flow can be written as follows [8, 9]:

$$\nabla \bar{\mathbf{v}} = 0 \quad (1) \quad \mu \nabla^2 \bar{\mathbf{v}} = \nabla p - \rho \mathbf{F} + \nabla \bar{\boldsymbol{\tau}} \quad (2)$$

$$\frac{\lambda}{c_p} \nabla^2 \bar{T} + \frac{\lambda}{c_p} (\bar{D} + \bar{Q}) - \nabla \bar{\mathbf{v}} \bar{T} - \nabla \bar{\mathbf{v}}' T' = 0 \quad (3)$$

Equations (1), (2) and (3) are written for averaged values of fluid velocity \mathbf{v} , pressure p , temperature T and mass density ρ . RANS equations cannot be solved without turbulence model. In analyzed case $k-\varepsilon$ turbulent model was used. It is two equations model, which include two extra transport equations to represent the turbulent properties of the flow [10]. For analyzed HT° machine it is necessary to take into account the rotor rotation and radiation which have a significant contribution in the heat flow. The rotor rotation can be solved using the moving reference frame equations, whereas the rest of machine's parts can be solved with the stationary frame equations [10]. Radiation can be included by additional radiation model (Discrete Ordinates or Surface-to-Surface). This method can be used to calculate the radiation inside the machine. For external walls the simplest approach is using mixed boundary condition for energy equation (2) with the surface emissivity coefficient ε_r . The convective component of this boundary condition can be determined from empirical formula which is based on dimensionless Rayleigh and Nusselt numbers. 3D coupled thermal-fluid model is prepared using Ansys Fluent package. This model includes such parts as shaft, bearings and housing. These elements participate in the heat flow in the machine; therefore, they must not be omitted. Ansys Fluent package uses the finite volume method. The finite volume mesh of the HT° machine model has over 5 million elements.

Heat sources in the analyzed machine are the power losses. To analyze of the losses the time-stepping 3D finite element method (FEM) is used. The power losses in the core, permanent magnets and windings of HT machine were calculated. The detailed description used for calculating the losses is presented in the paper [8]. In equation (3) the heat source is presented as heat source density Q which can be calculated from following formula:

$$Q = \frac{\Delta P}{V} \quad (4)$$

where ΔP is power losses taken from electromagnetic analysis and V is a volume of motor's part where the power losses were generated.

In order to obtain excitation for the thermal model, calculations of the electromagnetic field were made using the Opera program [11, 12]. For the purpose of the 3D simulation a quarter of the machine has been considered to benefit from the magnetic symmetry. The windings are modelled by connections to external resistances. The time stepping analysis was performed assuming constant speed of rotation of the rotor. The 3D mesh contains 4.264778 million elements in total. In the conductive areas, the elements size was chosen to be less than one-third of the penetration depth. Moreover, the distribution of the density of the mesh is greater than to correctly reproduce the effect of rotation of the rotor relative to the stator. To reduce the computation times the simulations were performed on a virtual machine with eight cores. Next the core losses are calculated as an average value taken from all available time snapshots. A number of sample points in time were chosen to allow for the subsequent Discrete Fourier Transform (DFT) analysis. Using the values of components of magnetic flux density in each mesh element calculated at sample

points, the DFT analysis was performed in order to assess the contribution of higher harmonics. The number of calculated harmonics was selected according to the Nyquist–Shannon sampling theorem as half of the number of sample points. The calculation of losses necessitated extrapolation of the specific loss characteristic of the material for frequencies above 5000Hz. This extrapolation used the measured values in the range 50-5000Hz and had the form:

$$w_{Fe} = k_e f^2 B^\alpha + k_h f B^\beta \quad (5)$$

In the case of the Vacoflux 48 material the coefficients in (5) have the following values: $k_h=2.22256E-02$, $k_e=1.358143E-5$, $\alpha=2.72582$, $\beta=1.14622$. The losses generated by the higher harmonics account for only 11.4% of the fundamental loss, which suggests that the magnetic circuit has been properly configured.

IV. SOME RESULTS AND CONCLUSIONS

Using the coupled thermal-fluid-electromagnetic model the repartition of the temperature outside and inside the machine for the various designs and material were calculated. Figure 4 shows an example result of the distribution of the temperature in the all PMSM machine for 2 variants surface mounted magnets and embedded magnets with and without wedges.

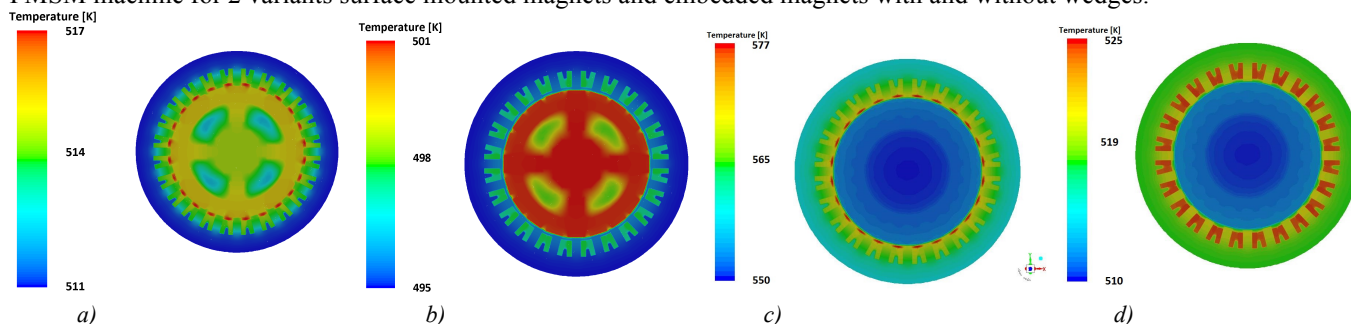


Fig.4. Temperature distribution in the motor - cross section XY: a) variant 1 with wedges, b) variant 1 without wedges, c) variant 2 with wedges, d) variant 2 without wedges

Basing on the results of simulations three prototypes were constructed, the first one is a PMSM with the surface mounted permanent magnets, second one with interior magnets in the rotor and third one is a SRM. The comparison of simulation results and measurement has shown good compatibility, temperature differences do not exceed 6°C. The tests carried out allowed us to state that synchronous motors with permanent magnets can be used in the case of an ambient temperature of not more than 300°C. For higher temperatures we recommend using of the variable reluctance machine. The comparison of simulation and measurements results and comparison of ownership and selection of a suitable machine for specific working conditions will be presented in the full version of the paper.

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