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# HIGH TEMPERATURE MACHINES: A COMPARISON BETWEEN CERAMIC-COATED WIRES AND ANODIZED ALUMINUM STRIPS

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**Abstract**—The paper proposes a comparative approach of two wire technologies for making coils of compact high temperature machines. The first technology is based on ceramic-coated round wire associated with a specific cement. The second one uses anodized aluminum strips. The advantages and drawbacks of the two technologies are compared, considering the machine global performances at high temperatures. The paper also compares the distribution of electric stresses due to the fast fronted voltage pulses of the PWM inverter.

**Keywords**—High temperature machine, Inorganic insulation, Thermal equivalent circuit, High frequency equivalent circuits.

## I. INTRODUCTION

Electrical machines are widely used in industries and transports to perform efficient and accurate controls of complex mechanical systems. This advantage is however limited by the maximal running temperature of electrical machines, as it is directly linked to the thermal limits of the polymers used in the electrical insulation system (EIS) and the expected lifetime [1]. Consequently, classic electrical machines cannot work in very hot areas, where the temperature exceed  $250^{\circ}\text{C}$ , as, for instance, near an aircraft turbine. Design of machines able to work permanently under high temperature stress (over  $250^{\circ}\text{C}$ ), is nevertheless possible with inorganic EIS made without any polymers [2]. These high temperature ( $\text{HT}^{\circ}$ ) machines are designed with rigid coils made with ceramic coated wires and  $\text{HT}^{\circ}$  cements used as potting materials. Such coils are able to withstand  $500^{\circ}\text{C}$  [3]. For  $\text{HT}^{\circ}$  machines, the design process is very different than for classical ones, because the inorganic coils are rigid objects. The magnetic core must be adapted to coils, distributed windings are very difficult to build.

Generally speaking, the rated power of an electrical machine depends on the rotor speed, the flux density in the air-gap and the current density in active conductors [4]. The same principles apply for  $\text{HT}^{\circ}$  machines, but with higher current densities because of the higher internal temperature gradients. The heat flows are more intense for the same motor sizes. The comparative study relies on a simplified thermal model which computes the temperature of the critical parts of the machine. Another model, based on a high frequency (HF) equivalent circuits, compares voltage stresses due to the fast fronted pulses of the PWM inverter.

## II. COMPARISON PRINCIPLE OF THE WINDING TECHNOLOGY

The assessment of the power density differences due to the two  $\text{HT}^{\circ}$  insulation technologies is performed using two identical Permanent Magnet Synchronous Machines (PMSM). The rotors are equipped with the same surface-mounted high performance magnets. The only difference is the stator coil technology. Both machines are made using the widespread “24 teeth / 20 poles” structure for high power density applications

[5]. Each stator tooth receives a prefabricated coil. All coils have the same number of turns. The 24 stator coils form 3 phases of 8 coils connected in series. The winding directions are chosen to get a dominant 20-pole rotating field in the air-gap, when a balanced 3-phase system feeds the machine. Fig. 1 shows the stator of the machine made with ceramic-coated wire coils embedded in a  $\text{HT}^{\circ}$  potting cement. The general aspect of the stator made with anodized aluminum strips is very similar.



Fig. 1. Stator of a  $\text{HT}^{\circ}$  PMSM made with 24 rigid inorganic coils. The picture was made before closing the slots with metallic wedges.

Fig. 2 shows the details of  $\text{HT}^{\circ}$  coils on a stator tooth. Each 25-turn coil is made of two layers of 1 mm diameter ceramic-coated round wire. The ground insulation and the interlayer one are made of mica. A potting  $\text{HT}^{\circ}$  cement immobilizes the turns and an external piece of fiberglass protects the cement. Fig. 3 shows the alternative  $\text{HT}^{\circ}$  technology made of 25 turns of a flat anodized aluminum strip. The strip thickness is adapted to fit the slot width and to get the same coil global thickness. The alumina layer thickness of the studied anodized strip is  $5\ \mu\text{m}$  [6]. The mica ground insulations are identical.

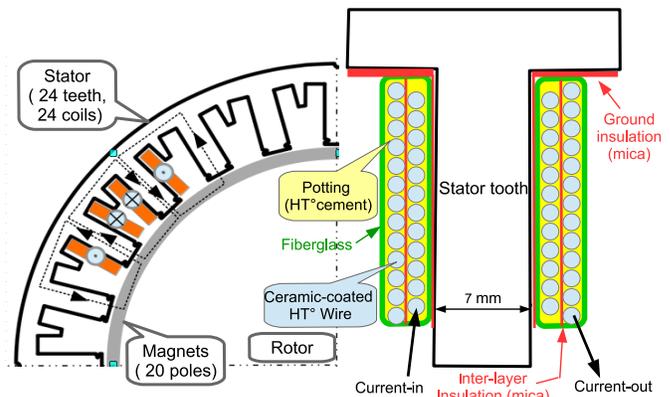


Fig. 2. Details of the first machine technology (inorganic coils made with a ceramic-coated  $\text{HT}^{\circ}$  wire).

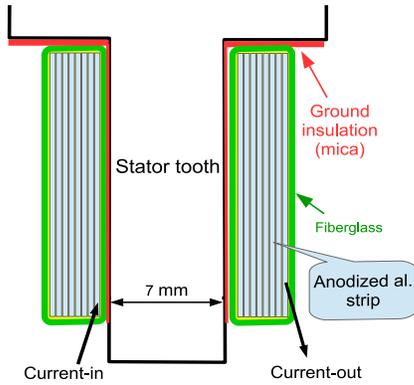


Fig. 3. Second machine technology: anodized aluminum strip.

### III. THERMAL COMPARISON

The simplified thermal equivalent circuit of Fig. 4 is used to estimate the motor internal temperatures. The model is based on three simplifying hypothesis:

- The thermal flows between nodes are proportional to the temperature differences;
- Only 4 temperatures in critical parts are considered: the rotor magnets (M), the windings (W), the stator core (Iron-I) and the motor frame (F);
- The cooling system is a standard fan that creates an external airflow through the fins of the stator frame.

The rated current of machines is obtained when the maximum temperature is reached in a critical part (M or W).

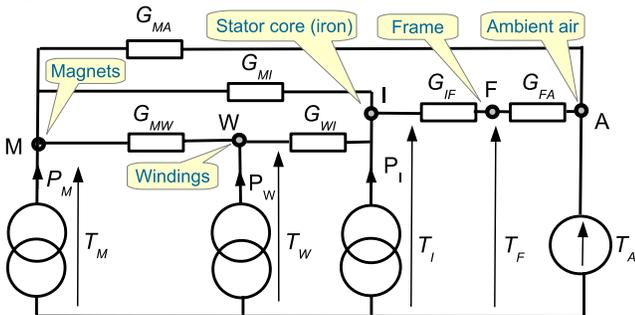


Fig. 4. Simplified thermal equivalent circuit of a PMSM at steady state with heat sources ( $P_M$ =magnet losses,  $P_W$ =winding losses,  $P_I$ =Iron losses) and thermal conductances.

The magnets are glued on a metallic rotor. Consequently, a part of the magnet losses ( $P_M$ ) flows directly outside the motor by the metallic shaft ( $G_{MA}$ ). The other part crosses the air-gap toward the stator ( $G_{MW}$  and  $G_{MI}$ ). To compare both technologies, the only difference is the conductance  $G_{WI}$  between the conductors in windings (node W) and the stator iron (node I). The aluminum strip technology yields a radial thermal flow in aluminum, higher than the first technology where the heat flow must cross the cement potting.

The inverter command is adapted to the load for obtaining the same power factor (0.8). Therefore, the stator current ( $I_S$ ) is proportional to the mechanical load and the Joule losses in windings ( $P_W$ ) also depend on the on the load:

$$P_W = 3R_S I_S^2 \quad (3)$$

The resistance  $R_S$  and the stator losses depend on the winding temperature. An iterative method is implemented to estimate the Joule losses and the temperatures, considering

non-linear effects with a polynomial form, rather than a constant temperature coefficient.

### IV. DIFFERENCES BETWEEN THE VOLTAGE DISTRIBUTIONS BETWEEN TURNS

PWM inverters always control the high-performance compact machines. Consequently, fast-fronted voltages are imposed to the input of the connection cable. These fast edges impose short transient and voltage spikes to the motor winding. These spikes can be computed using the global high frequency (HF) equivalent circuit of the whole system (cable + motor) [7]. The comparison between the two HT° technologies is made considering a 5-meter length connection cable and a single coil. The HF equivalent circuit is made of 5 T-cells for the cable and 24 RLC cells for the coil (one per turn). A Spice solver performs the transient simulation. 2D finite-element simulations determine capacitances, turn and mutual inductances.

### V. CONCLUSION

Preliminary results of the thermal comparison shows that the HT° coils made with aluminum-anodized strips offer a better filling of the stator rectangular slots than round wires. The thermal conductance between the heart of the coil and the stator core ( $G_{WI}$ ) is higher. However, the resistance increase with temperature is slightly higher for aluminum. Simulations show that the second solution is better for medium temperatures until a limit that depends on the geometry.

Turn-to-turn capacitances are much higher for coils made with anodized-aluminum strips. This parameter drastically changes the behavior yielding a better voltage spikes distribution. However, the current spikes are larger for short connection cables. Results of section 3 and 4 will be detailed in the full paper.

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