**Cryogenic Cooling Impact on Induction Motors**

**Introduction**

In the past few years many efforts have been made towards the electrification of transportation systems.  
Europe’s Vision for Aviation report, identified the electrification of commercial aircraft as a way to reduce the emissions of , and noise, by 75%, 90% and 65%, respectively, by 2050.  
This led to the need of higher requirements for electrical machines, such as higher specific torque/power and higher efficiencies. To achieve these challenging ideas, we have to use advanced material like superconductors. These materials may achieve power density of 20/30 KW/Kg.

**Why cryogenic cooling?**

The operation of the machines in a cryogenic environment has shown considerable improvements to specific torque and efficiency. This results in a significant decrease of Joule losses in the stator and rotor conductors, but also an increase in iron core losses, due to eddy current. On the other hand, compared with the eddy current losses increase, the change of the BH curve and hysteresis losses of iron cores are significantly lower for cryogenic temperatures.  
Cryogenic induction machines (IMs) have been at the forefront of this research due to their high operating reliability in cryogenic environments and their low cost.

**Experimental information**

Table

Description automatically generatedIn this experiment, a small conventional machine is subject to cryogenic operation at 77K, within LN2 submersion to verify its increase of performance. The following table shows the machine’s specifications.

It is known that the effect of temperature in the iron core is due, for the most part, to the increase of electric conductivity, associated with the eddy current losses and, to a smaller extent, associated with the hysteresis losses. For typical laminated iron core materials, such as M400-50A and M43, there is an increase between 10 % to 16 % of iron losses when the magnetic core is submerged in liquid nitrogen, at a frequency of 50 Hz.

Under cryogenic tests, the IM under analysis was kept immersed in liquid nitrogen in an expanded polystyrene (EPS) foam container.  
  
The experimental setup was developed in a vertical position to facilitate the mechanical coupling between the induction machine and the 1kW calibrated DC machine used as load.  
  
Most lubricants used today in standard bearings can handle a very wide spectrum of temperatures, usually from -50˚C up to 200˚C, but its grease freezes under LN2 temperature. Therefore, the grease had to be removed using an acetone bath. In addition to that, LN2 has good lubricant properties.  
  
To verify the temperature of the machine’s active parts under cryogenic conditions, the stator and rotor temperatures during the testing activity were measured using cryogenic temperature sensors.  
  
During this test three cryogenic temperature sensors were used to monitor the temperatures at the machine air gap, at the top and at the bottom surfaces of the rotor, respectively.  
  
The experimental results indicate that under cryogenic conditions the active parts of the IM remain close to 77K.

Table

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The above table lists the obtained equivalent circuit parameters and the mechanical losses. The results for the no-load tests show an increase of mechanical losses from 1.96 W, at ambient temperature, to 3.83 W, at cryogenic conditions, both without the bearing grease. Moreover, for the same level of magnetization, the iron losses increased about 11.6 % under cryogenic conditions, corresponding to a decrease of 10.4 % of the equivalent iron losses resistance.  
  
The values measured for the stator resistance are equal to 1.1 Ω and 0.175 Ω for the ambient and the cryogenic temperature, respectively. This corresponds to a decrease of 84.1 %, when operating under cryogenic conditions. For the rotor resistance, a reduction of 73.4% has been obtained from ambient temperature to cryogenic conditions.

The induction machine was tested under 20, 30, 40 and 50 Hz. The stator voltage was regulated to assure the same magnetizing flux for all frequencies. there is an increase in mechanical losses under cryogenic conditions, with an average offset of 1.83 W. These drag losses are due to the friction with LN2.  
  
To verify the stability of the IM when submerged in liquid nitrogen, load tests were performed for 1 hour. During this test, the machine operated without experiencing abnormal vibrations. At ambient temperature operation, the maximum current was limited to the rated one. The maximum efficiency of 63% was obtained for a stator current of 3.3 A, a torque of 0.72 Nm and a speed of 1353 rpm, corresponding to a mechanical power equal to 102 W. Under these conditions, the stator and rotor Joule losses, the iron losses and the mechanical losses correspond to 35.9 W, 9.6 W, 12.5 W and 1.96 W, respectively.   
  
The maximum efficiency of 85.2% was obtained for a stator current of 6.7 A, a torque of 1.95 Nm and a speed of 1441 rpm, and a mechanical power of 294.3 W. When compared with the ambient temperature operation, there is an increase of 171% of nominal torque and 189% of nominal mechanical power. Due to the high reduction of stator and rotor resistances, the impact of these losses on the machine operation is drastically lower.  
  
For the same torque, under cryogenic conditions the efficiency increases from 63.0% to 79.7%, mostly due to stator and rotor losses reduction. There is a slight increase of stator current due to the increase of the no-load current (I0amb = 2.5 A for ambient and I0cryo = 3.0 A for cryogenic conditions) due to the higher iron losses and a higher magnetizing current due to the higher magnetization level of the machine core because of the reduced stator voltage drop.  
  
In addition, under cryogenic conditions, the maximum mechanical power was 481.5 W (3.8 Nm) with an efficiency of 73 %, corresponding to an increase of 372 % of mechanical power when compared with the ambient temperature conditions. For this machine, no thermal restrictions were verified, due to the high capacity of heat extraction of liquid nitrogen. Therefore, this maximum mechanical power point is only limited by the torque-speed sable zone.

**Conclusion**

In this work, an experimental assessment of the influence of cryogenic cooling in a fractional kilowatt induction motor, originally designed for ambient temperature operation, is performed. The experimental findings supported by the analytical procedure show that, in this fractional kilowatt induction motor, under ambient conditions, the stator Joule losses are the highest source of losses. Therefore, the high reduction of the stator resistance contributed to a high increase of efficiency, for the same stator current. Comparing the ambient temperature and cryogenic conditions, the maximum efficiency increased from 63 % to 85.2 % and the nominal torque increased from 0.72 Nm to 1.95 Nm. In addition, due to the excellent cooling capacities of the liquid nitrogen, that keeps the machine active parts below 77 K during operations, no thermal limitation was found for the whole stable zone of the torque-speed characteristic. there are few results of small/medium IMs, the authors decided to extend the proposed methodology of analysis to motors in the 1-15kW range, both considering conventional and cryo-designed machines, in future research works.