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2. Introduction

Like in many other situations in life, the right level of cool can mean the difference between keeping things running smoothly and suffering a heat-induced breakdown. When an electric motor is in operation, the rotor and stator losses generate heat which must be managed through an appropriate cooling method. Efficient cooling has a significant impact on the lifetime of your motor. This is especially the case for the bearings and the insulation system, which are the components most vulnerable to overheating. In addition, long-term overheating can cause metal fatigue.

This basic rule of thumb illustrates the relationship between heat and lifetime:

- The lifetime of your motor's isolation system is divided by two for every 10°C over the rated temperature and multiplied by two for every 10°C below.
- The lifetime of your motor's bearing grease is divided by two for every 15°C over the rated temperature and multiplied by two for every 15°C below.

In addition to ensuring the health of the motor, maintaining optimal temperature levels are important to avoid efficiency reduction in general.

There are many cooling options available for electric motors. The optimal choice depends on your application, where the motor is mounted, the operating environment and several other factors.

In the past few years considerable efforts, from the industrial and research communities, have been made towards the electrification of transportation systems. These efforts have been aided by regulatory bodies, which, not only have been imposing higher efficiency standards for the manufacturing and design of new machines, but also identified the need for more measures regarding policy and long-term commitment. The EU, in Flightpath 2050: Europe's Vision for Aviation report, identified the electrification of commercial aircraft to reduce the emissions of CO_2, NO_x and noise, by 75%, 90% and 65%, respectively, by 2050. (Bucho, Fernandes, Biasion, Vaschetto, & Cavagnino, 2022)

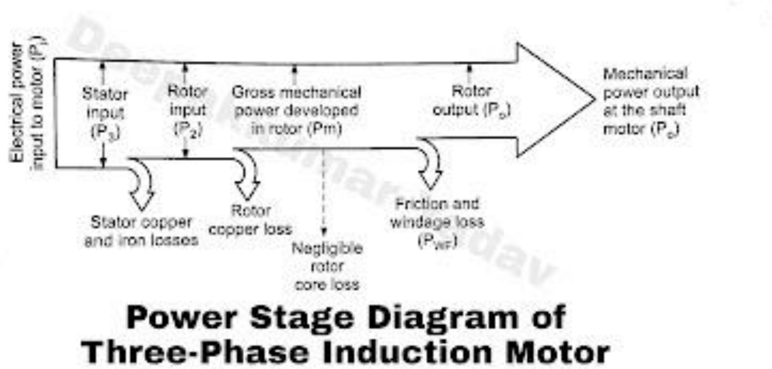


Figure 1

The power flow diagram explaining the losses in induction motors.

(Yadav, 2021)

3. Cooling means for electric machines

Overview of cooling methods

Cooling an electrical apparatus is not an easy task, that is, although, as we increase the size of the motor the surface area available to release the generate heat increases by square the dimensions, however, the amount of heat generated itself increases proportionally to the increase in total volume which is roughly proportional to cubic the increase in dimensions. In addition to that, the physical and economic factors of the motor manufacturing and operation demand that the motor size decreases as much as possible. Thus, cooling technologies have been developed to efficiently cool the machines. (Umans, 2014)

Common cooling medium markings: "air" is A; "water" is W. In case, the cooling medium air mark A, it can be omitted.

The cooling mode is marked as follows: code IC + cooling circuit arrangement + primary cooling medium + driving mode of primary cooling medium movement + secondary cooling medium + secondary cooling medium movement. (Common cooling method for high voltage motors, n.d.)

Cooling medium code interpretation

The cooling medium code is “flag letter” + “cooling circuit arrangement code” + “primary cooling medium code” + “primary cooling medium motion pushing method” + “secondary cooling medium code” + “secondary cooling medium motion driving method”.

For example, IC86W is fully labeled IC8A6W7. The specific meanings are: “IC” is the logo letter (international general cooling symbol), “8” is used to represent the external cooler (using remote medium), and “A” is used to characterize the primary cooling medium air. (Can be omitted), "6" indicates that the primary cooling medium is driven by a separate component, "W" characterizes the secondary cooling medium water, and "7" characterizes that the secondary cooling medium is driven by a separate component or cooling medium system (cooling medium) For water and the pushing method is 7, the number 7 can be omitted).

Cooling method for the motor

In order to select the most appropriate cooling method that ensures the lowest possible cost and the highest efficiency, we must observe the loading characteristics of the motor. The following are some torque-speed characteristics for different loads:

1. Constant torque load

The load characteristics are constant torque below the base speed and constant power above the base speed. That is, during low-frequency start-up and low-frequency operation, the variable frequency speed control motor still outputs a large torque (rated torque). At this time, if the fan is cooled (such as IC411 and IC611), the speed is low and the cooling condition is used. Deterioration, motor heating is very serious, it is necessary to add an independent forced cooling fan to the motor to ensure safe operation of all frequency bands.

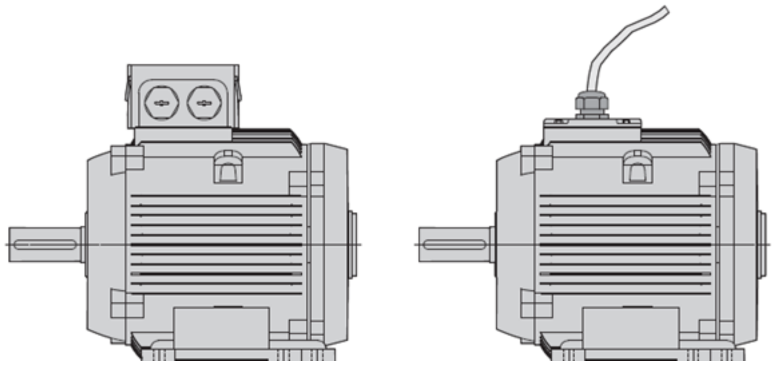
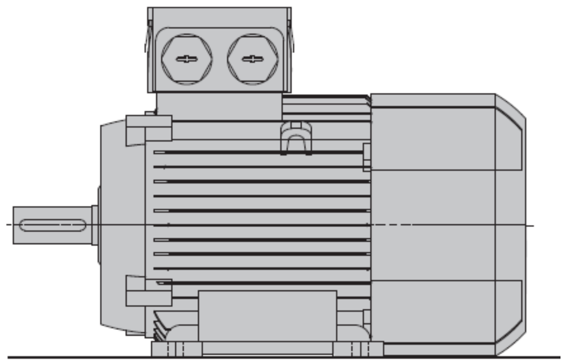
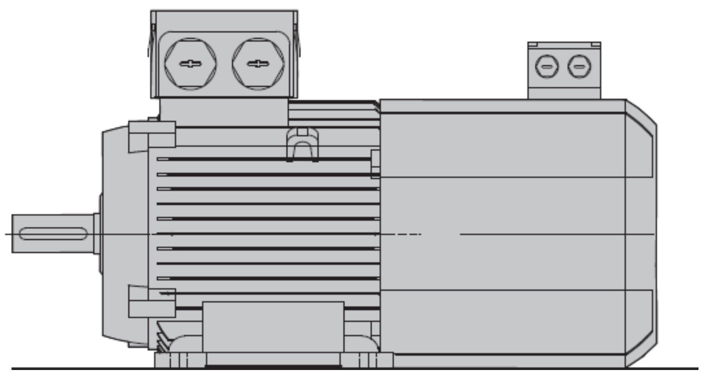
2. Fan, pump load

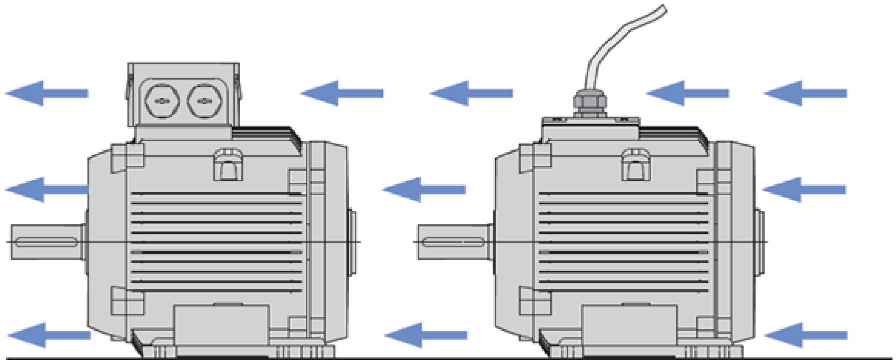
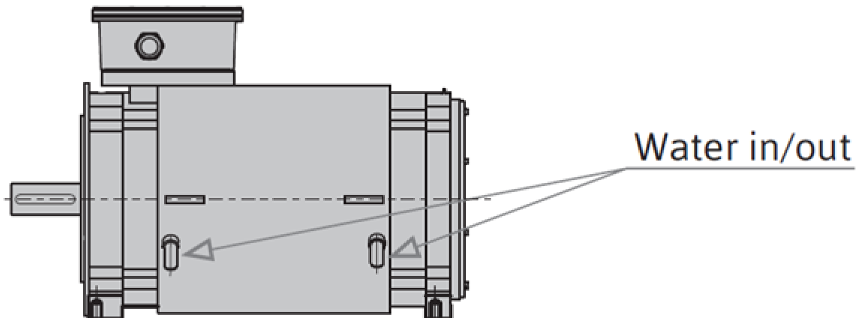
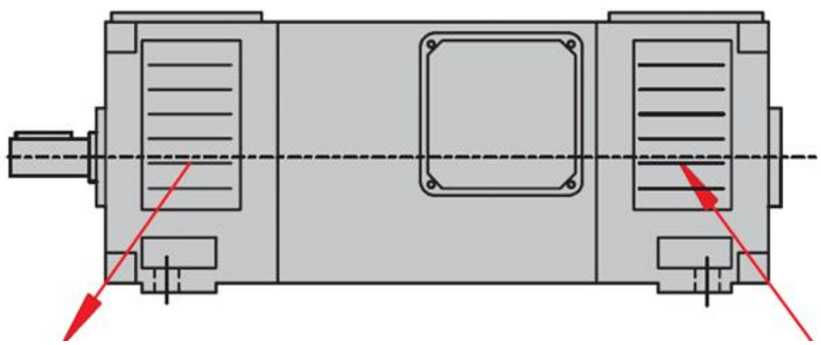
When the load of the variable frequency speed regulating motor is the load of the fan and the pump, the load torque varies with the square of the rotational speed (TL$\propto$n2), the load torque is small at low-speed operation, the output power of the motor shaft is very low, and the heat generation is also small. There is no need to worry about the heat dissipation problem of the variable speed motor at low speed. You can use the internal and external fan cooling methods IC411 and IC611, which is the theoretical basis for J to introduce the IC611 motor to customers.

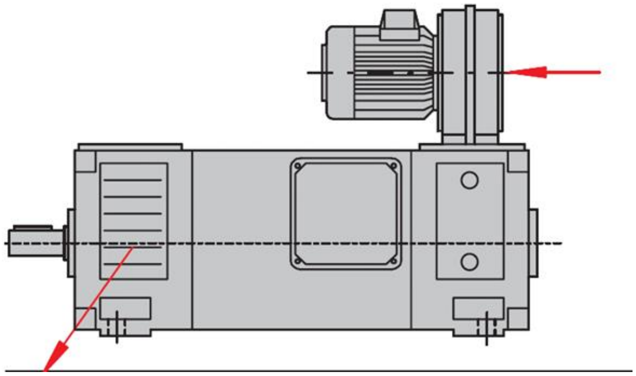
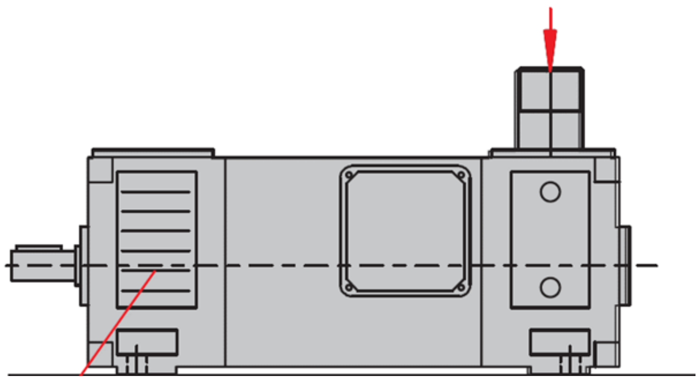
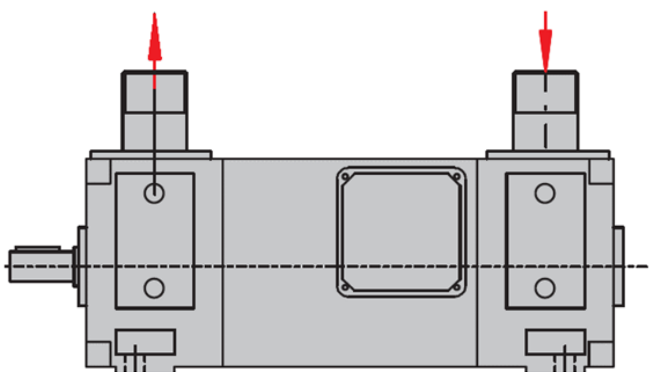
In conclusion, to select the appropriate method for cooling we must observe the loading characteristics of the machine as well as the surrounding environment. This way, we can ensure the safe operation of the apparatus. (How to choose the motor cooling method according to the actual working conditions?, 2018)

4. Cooling methods of motors according to IP number & voltage levels

LOW VOLTAGE MOTORS - Totally Enclosed (IP44 and higher)

 *Figure 2*	IC410 - TENV - Totally Enclosed Naturally Ventilated (No fan)
 *Figure 3*	IC411 - TEFC - Totally Enclosed Fan Cooled (own fan ventilated)
 *Figure 4*	IC416 - TEFV - Totally Enclosed Force Ventilated (ventilated with independent fan) IC416A (axial fan) - IC416R (radial fan)

 *Figure 5*	IC418 - TEAO - Totally Enclosed Air Over (no fan-motor in air stream)
 *Figure 6*	IC71W - Jacket Water Cooled
 *Figure 7*	IC01 - Open circuit self-ventilated motor with integral fan on the shaft

 *Figure 8*	IC06 - Force ventilated motor with (radial) fan unit (fan unit can be also axial) IC06A (axial fan) - IC06R (radial fan)
 *Figure 9*	IC17 - Single pipe ventilated motor (air supplied from independent source)
 *Figure 10*	IC37 - Double pipe ventilated motor (Air supplied from independent source)
MEDIUM & HIGH VOLTAGE MOTORS	
Ribbed motors (IP44 and higher) can be:	

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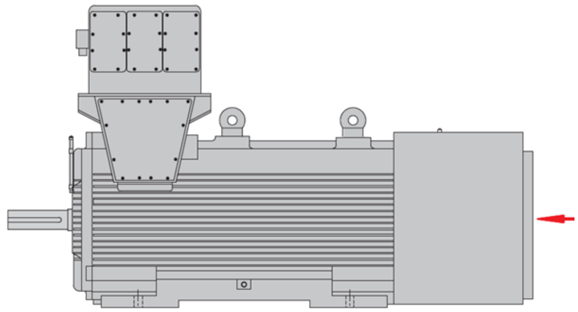
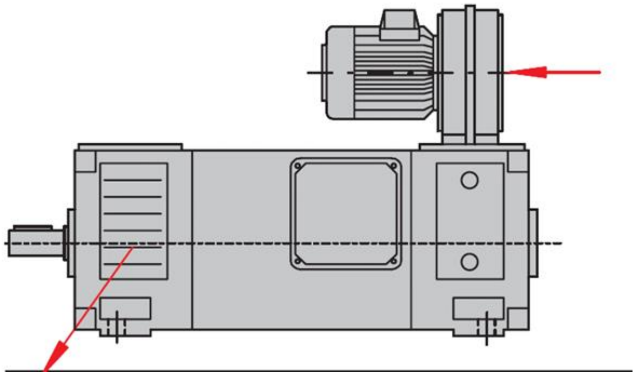
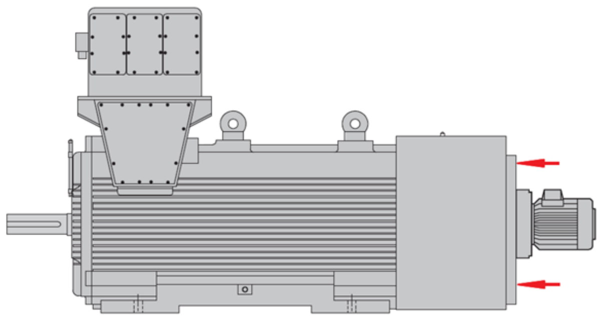
<tr><td>
Figure 11</td><td>IC411 - TEFC - Totally Enclosed Fan Cooled

(Own fan ventilated)</td></tr>
<tr><td>
Figure 12</td><td>IC416 - TEFV - Totally Enclosed Force Ventilated

(Independent fan ventilated)

(Fitted with radial fan unit)</td></tr>
<tr><td>
Figure 13</td><td>(Fitted with axial fan unit)</td></tr>
<tr><td colspan="2">Motors with smooth cast iron or steel fabricated frame can be:</td></tr>
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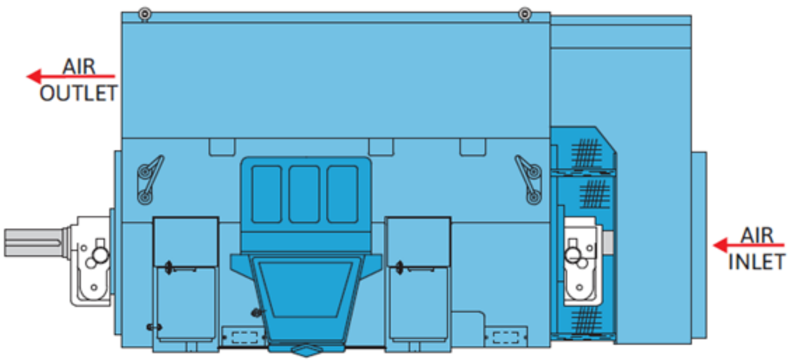
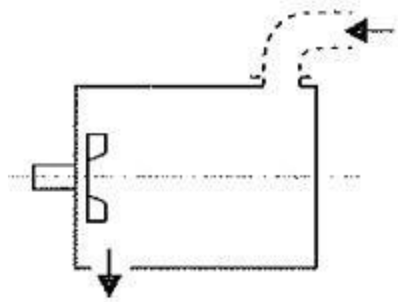
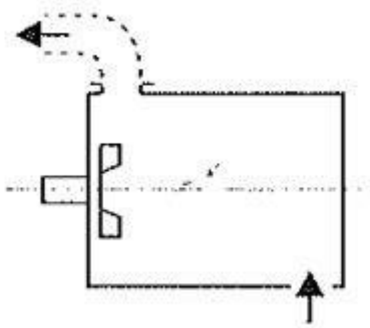
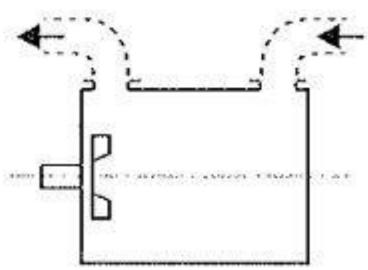
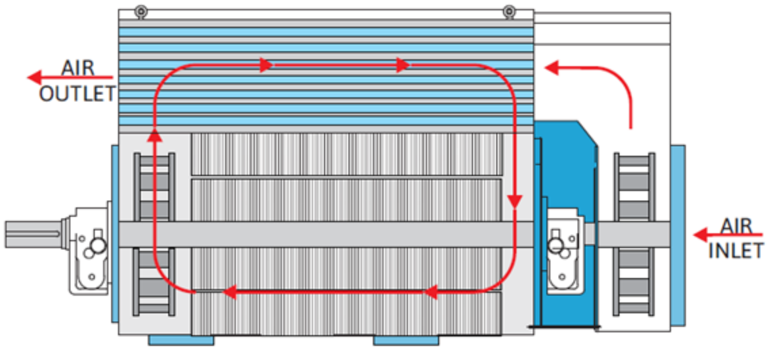
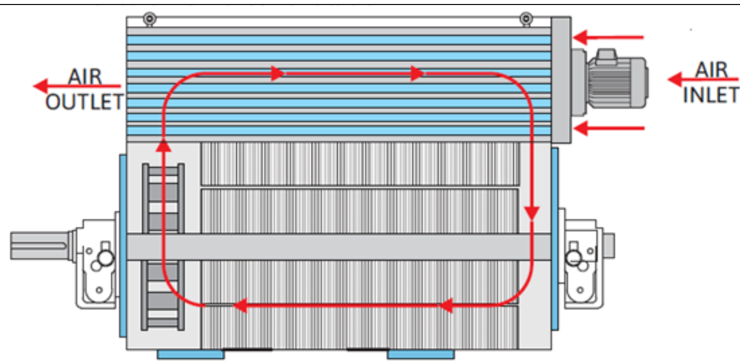
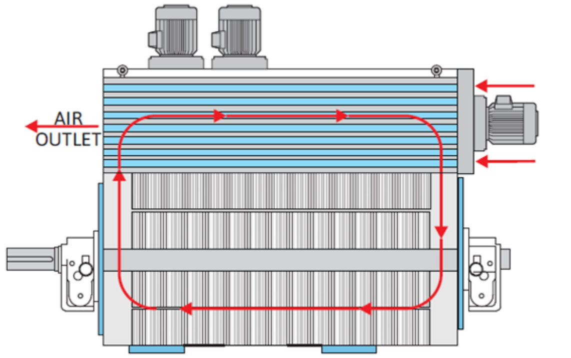
 *Figure 14*	IC01 - Open circuit ventilation
 *Figure 15*	IC11 - Self-ventilation with air inlet duct (cooling circuit) (media motion drive).
 *Figure 16*	IC21 - self-ventilating with air ducts.
 *Figure 17*	IC 31 - Supply and removal via pipe or duct. The cooling medium is the supplied medium

 *Figure 18*	IC611 - (formerly IC 0161) - CACA - Air-Air cooling with integral fan on motor's shaft inside stator and heat exchanger with open external circuit with fan on motor's shaft.
 *Figure 19*	IC616 - Air-Air cooling with integral fan on motor's shaft inside stator and heat exchanger with open external circuit with force ventilation.
 *Figure 20*	IC666 - Air-Air cooling with forced fan system inside stator and heat exchanger with open external circuit with force ventilation.

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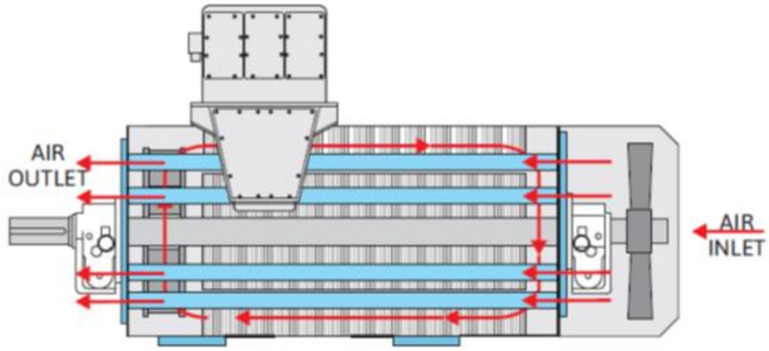
<tr><td>

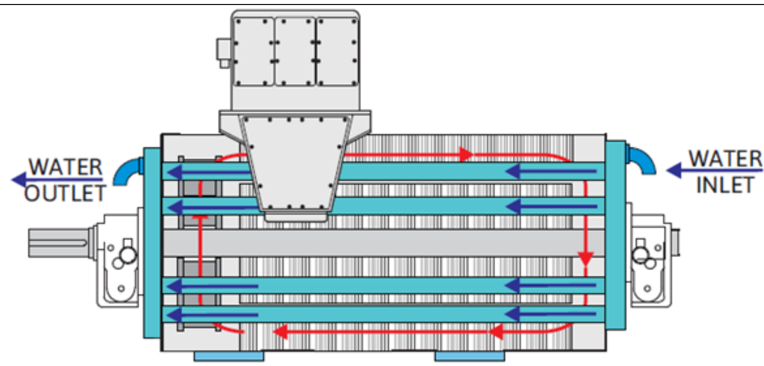
Figure 21</td><td>IC511 - Air Pipe cooling with fan on motor's shaft and open circuit piping in motor's stator.</td></tr>
<tr><td>

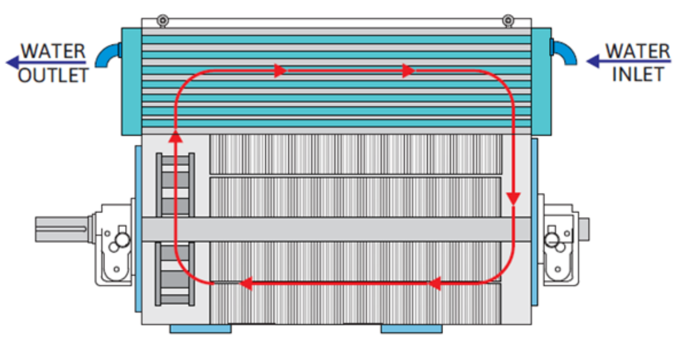
Figure 22</td><td>IC31W - Air-Water cooling with inlet and outlet pipe or duct for cooling water circulation.</td></tr>
<tr><td>

Figure 23</td><td>IC81W - Air-Water cooling with integral fan on motor's shaft inside stator and water-cooled heat exchanger.</td></tr>
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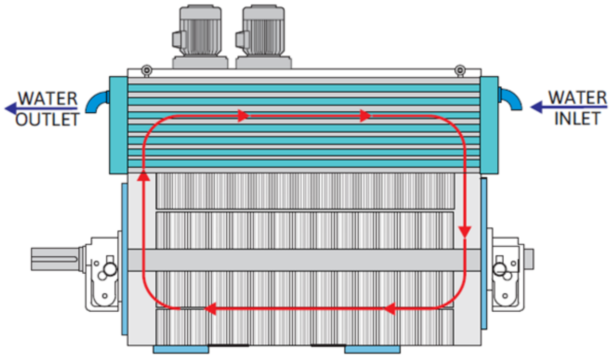 *Figure 24*	IC86W - Air-Water cooling with force ventilation system inside stator and water-cooled heat exchanger.

(Limited, 2017) (Common cooling method for high voltage motors, n.d.) (How to choose the motor cooling method according to the actual working conditions?, 2018) (Cooling of electrical machines, n.d.)

5. A comparison between two models of three phase induction motors (Menzel co. & Omemotors co.)

	Menzel	Omemotors
Cooling method	IC 81W - IC 86W	IC411
Voltage rating	Nominal voltage at 50 Hz • **Low voltage:** 380 V, 400 V, 440 V, 480 V, 500 V, 525 V, 575 V, 690 V • **Medium and high voltage:** 2.300 V, 4.160 V, 6.000 V, 6.600 V, 11.000 V, 13.200 V, 13.800 V Nominal voltage at 60 Hz • **Low voltage**: 380 V, 400 V, 500 V, 690 V • **Medium and high voltage:** 3.000 V, 3.300 V, 5.000 V, 5.500 V/	Nominal voltage at 50 Hz • **Low voltage:** 380 V, 400 V, 440 V, 480 V, 500 V, 525 V, 575 V, 690 V • **Medium and high voltage:** 6 kV (3 kV,3.3 kV, 6.6 kV on request) Nominal voltage at 60 Hz *In request*

	6.000 V, 6.300 V, 6.600 V, 10.000 V, 10.500 V, 11.000 V	
Frame size	315-900	355-560
Power range (kW)	25000	160 - 1600
Protection classes	IP23, IP 55, IP 67	IP54, IP55
Construction type	IM B3, IM V1 (special designs possible at any time)	IMB3 (IMB35, IMV1 on request).
Image		
	Figure 25	*Figure 26*

(Water-cooled squirrel cage motors (IC 81W and IC 86W), n.d.)

(OMV IC411 High Voltage Series, n.d.)

6. Cryogenic Cooling Impact on Induction Motors

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 to reduce the emissions of CO2, NOx, 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

In 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.

NOMINAL VALUES AND DESCRIPTION OF THE TESTED MACHINE

Induction machine	Rated Values
Voltage, (V)	40
Current, (A)	3.6
Power, (W)	90
Speed, (rpm)	1350
Frequency, (Hz)	50
cos(φ)	0.61
Materials	
Rotor cage	Aluminum die-cast
Stator windings	Copper distributed
Iron core	FeSi Alloy

Figure 27

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.

EQUIVALENT CIRCUIT PARAMETERS AND MECHANICAL LOSSES FOR THE TESTED IM AT AMBIENT AND CRYOGENIC TEMPERATURES

Parameter	Amb. Temp. (20°C)	Cryo. Temp. (77K)	Difference
R_{fe}, (Ω)	116.4	104.3	-10.4%
X_m, (Ω)	7.33	7.24	-1.2%
R_S, (Ω)	1.10	0.175	-84.1%
R'_R, (Ω)	0.914	0.240	-73.4%
X_S, (Ω)	0.532	0.532	+0.0%
X'_R, (Ω)	0.532	0.532	+0.0%
$P_{losses\ mec}$, (W)	1.96	3.83	+95.4%

Figure 28

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 □ and 0.175 □ 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 stable zone.

7. Conclusion

In this work, several methods of traditional and non-traditional methods of electric machines were discussed starting from self-cooling machines to more advanced cryogenic methods. In addition, we discussed the meaning behind IC codes and the methodology behind naming the cooling mode using letters and numbers (e.g., IC31W). Furthermore, we discussed in some detail the cooling method of cryogenic cooling using liquid nitrogen (LN2), 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.

8. Table of figures

9. References

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