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Evolution impact of electrical insulation systems in high power electrical machines

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Abstract- The paper deals with the history and evolution of electrical insulation systems, beginning with the discovery of insulation with the first experiments on electricity. Then, the aim is to analyse the use of insulation in electrical machine windings and the definition of the different parameters for the characterisation. Thereafter, this paper compares the thermal performance of the turn-to-turn insulation in several historic periods to demonstrate their improvements and the possible impact on the machine's sizing.

I. INTRODUCTION

It is in the 18th century, that the discovery of electrical insulation is assigned by the historians to Stephen Gray. It was with the discovery of electrical conduction and the first experiments that insulating materials are studied.

Gray's experiments allow separation of conductive and insulating materials, for example, glass and silk as insulating materials and brass and iron as conducting wire [1].

It is from 1884 that research will progress, with the creation of the AIEE (American Institute of Electrical Engineers) for the main aim of advancing "the theory and the practice of electrical engineering and of the allied arts and sciences and the maintenance of a high professional standing among its members." [2]. There is therefore the creation of research teams to study electrical insulation systems [3].

Nowadays, in electrical machines and typically, the electrical insulation systems are also used to prevent short circuits between conductors and the magnetic circuit. Another purpose is to ensure transmission of the heat released by the conductors to the parts of the magnetic circuit, also the impregnation makes it possible to give a rigidity to the winding, to avoid vibrations despite the magnetic forces that it can be subjected to [4].

In electrical machines, two types of winding can be identified. The first one, for low power machines, less than 100kW, supplied below 600V is named random winding, mainly made of round wire. The second one, for high-power machines and supplied more than 600V, usually high-voltage, consists of a flat conductor with a generally flat copper plate, is called form-wound coils.

The machine windings generally consist of three types of insulation:

- Turn-to-turn insulation, nearest to the conductor, to avoid short circuits between the wires.

- Groundwall insulation, between the conductors and grounded stator or rotor core for separates this, and avoid short-circuits between the winding and the magnetic circuit;
- Winding impregnation, used to fill the remaining air spaces between the coils, to solidify it and to give rigidity to the coil heads for mechanical strength [4] [5].

The improvement of insulation is characterised by several things: the thickness, the voltage resistance and the temperature performance, the last point is presented in this article for the turn-to-turn insulation for random winding.

II. TEMPERATURE PERFORMANCES OF THE TURN-TO-TURN INSULATION

A. Old insulation

In the early 1900s, natural fibre materials are mainly used for winding insulation. The most frequently used method of insulation is cotton wrapping. However, other natural fibre materials are used such as linen, silk, wool and later asbestos. This cotton wrapping can be single, but it is usually lined or tripled to prevent some faults during the application, and the important potential difference between the conductors [6]. At the beginning of the 1900s, it was observed that the main short-circuits between conductors were caused by the mechanical strength of the insulation (vibrations for example), weakened by the rise in temperature inside the machine.

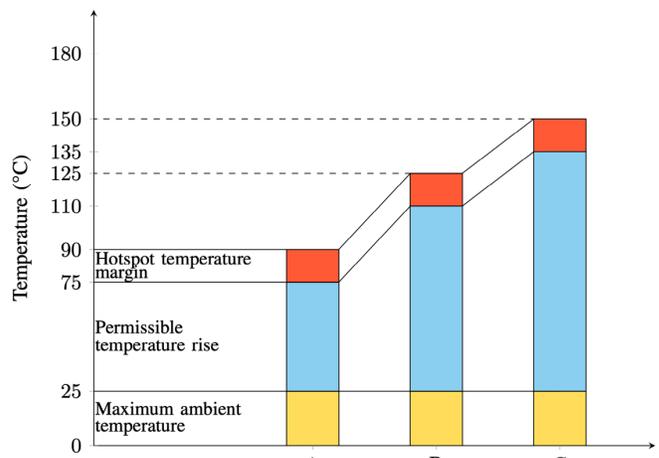


Fig. 1 Insulation class defined by Steinmetz in 1913

In 1913, the lifespan of insulation was not defined. Steinmetz conducts research to define the temperature performances of some insulating materials [7].

The figure 1 shows the first insulation classes divided into three groups:

- A : Natural fibre materials such as cotton, paper and natural resins.
- B : Asbestos and mica-based materials.
- C : Fireproof or heat-resistant mica based materials used in the construction of heaters and rheostats.

The materials groups A and B are those mainly used for winding, and C for the construction of heaters and rheostats. For cotton insulation only (column A), the maximum heating temperature can reach 90°C before it deteriorates. The addition of mica or asbestos increases the limit of use to 110°C.

B. Recent insulation

From the 1950s onwards, a considerable amount of research began to replace natural materials by plastic films and non-woven polymer fibres.

The discoveries made on insulation, made it possible to reduce their thickness, to increase their dielectric qualities, and their temperature resistance.

The new insulation systems require a different technique of deposition on the conductor, enamelling is used. The enamelling allows a homogeneous and calibrates removal of the insulation without default.

The figure 2 shows the most frequently used recent insulation classes for windings, with class H up to 180°C. The differences between the classes are explained by the chemical composition, for example, class F (150°C) is for low-density polyethylene insulation and class H (180°C) for high-density polyethylene [8].

For specific applications, there are materials with a very high temperature resistance, such as polyamide-imide (PAI) with a maximal temperature of 220°C, or polyimide at 240°C.

To withstand temperatures of 450°C-500°C, it is possible to use another technical system, with a thin layer coating of

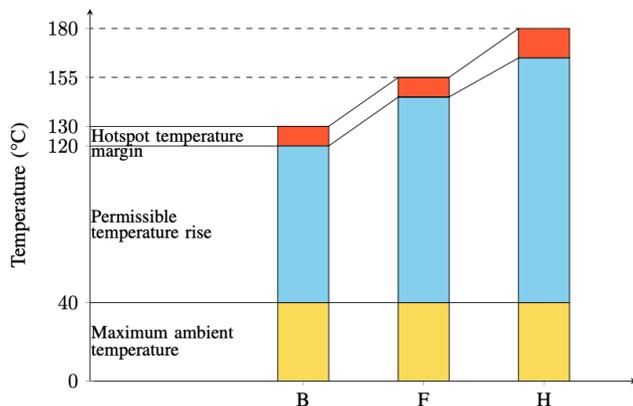


Fig. 2 Recent insulation class for maximum winding temperature

ceramic insulation for the conductor and a high temperature cement to consolidate the brittle ceramic insulation layer [9] [10]. But this insulation is fragile and therefore difficult to wind without damaging it.

C. Impact of electrical insulation

The electrical insulation evolution allows the increase of the voltage supply, the dielectric strength and the acceptable temperature. This concerns the high-voltage insulation and the fill factor improvement of copper in the slots [4] [6] [11]. Tables I and II give an overview of the improvement of electrical insulation.

It can be seen in table I that before 1960s the groundwall insulation was essentially made of micanite tube which is an assembly of thin flakes of mica stuck together with a flexible varnish, the tube thickness depends on voltage supply. The conductor insulation was composed of various papers and cotton. A few turns around the conductors were necessary. The new electrical insulation presented in the table II, is composed of several types of thin materials, each serves to protect the IM (turn-to-turn insulation, corona effect, mechanical protection).

TABLE I
Old Electrical Insulation

Localisation	Years	width (mm)	Composition
Flat copper	1926 / 1928	0,4	Coton wrapping or tape paper
	1955	0,3-0,4	
Winding / Groundwall	1926 / 1928	2,5-4	Micanite sheath / tube
	1955	2,5-3	

TABLE II
Recent Electrical Insulation

Localisation	width (mm)	Composition / laminating
Flat copper	0.3	Mica tape with polyester film
Winding	0.15	Mica paper with metallic salt accelerator and zinc naphtanate
Groundwall Corona effect	0.085	Conductor tape with polyester tape
Groundwall Finish tape	0.18	Glass and polyester and polyester felt with epoxy resin
Total Winding + Groundwall	0.415	Total insulation for the coil winding and groundwall

To the nearest of the conductor, the turn-to-turn protection is a base of mica paper with epoxy resin impregnation.

III. INFLUENCE ON MACHINE DESIGN

A. General evolution

The design of electrical machines depends on several factors. The internal dimensions of diameter and length are guided by the speed, namely the number of poles and the power. The dimensions of the stator section are determined by two main factors: firstly, the value of the induction in the air gap, which depends on the supply voltage. The induction in the various parts of the magnetic circuit, together with the quality of the magnetic steels, define the minimum lengths of the teeth and yoke; secondly, the permissible current density as a function of cooling, which determines the surfaces of the slots.

So, these two main components of the machine, together with improvements in materials, have made it possible to reduce the size of machines for equivalent power [12].

B. Impact on slot dimensions

Improving electrical insulation systems therefore makes it possible to improve current density because, as can be seen by comparing the figures 1 and 2, there is a possible gain of 90°C if we compare Steinmetz's 110°C class and the current H class 180°C. Therefore, more current can flow through conductors of equivalent size.

Then, from the point of view of thicknesses, the tables I and II present two examples of insulation used for high-power asynchronous machines, first in the 1950s for the table I and nowadays for the table II.

The gains in thickness are considerable: the thickness of the turn-to-turn insulation is reduced by 50% and for the insulation of the coils combined with that of the bottom of the slot, the thickness is 5 to 6 times less.

C. Refurbishment perspectives

The various gains described in the previous section do not only concern the sizing of new machines.

The renovation of electrical machines can also benefit from this development. A large number of old-generation electric motors from the 1950s are still in operation with their original windings.

The prospect of renovating the winding with a new winding and new insulation offers several advantages.

Firstly, by reducing the thickness of the insulation, the size of the conductors can be increased, and therefore the filling coefficient.

With more copper, operating at the same load point reduces Joule losses and heating.

Secondly, it is also possible to accept more heat thanks to a better insulation class. This makes it possible either to increase the current to get a little more power, or to improve the longevity of the machine with a stronger winding.

This aspect of renovation also has the advantage of having a reduced environmental impact, thanks to reduced Joule losses and higher efficiency at the same operating point.

IV. CONCLUSION

The evolution of electrical insulation systems has been allowed to increase their performances, that is the thickness, the voltage resistance and the temperature performances.

This paper presents the evolution of the thermal performance of insulation. The first insulation often based on natural fibres, did not exceed 90°C alone. Nowadays, thanks to the technique of enamelling and research on polymers, it is possible to reach 180°C or even 240°C for more specific insulation.

For the design of electrical machines, this improvement is beneficial, it allows the increase of the current density of the winding and therefore reduce its size. There is also a better mechanical strength of the insulation due to the application technical.

The better performances of insulation allow them to increase the size of the conductors and consequently to reduce their electrical resistance and improve the efficiency. Another possibility with better insulation is to reduce the size of the machines, which decrease the environmental impacts of the manufacture.

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