Design and Testing of a Steam-Resistant Insulation System for the Stator of a Low-Voltage Turbo-Generator Taking Thermal Aspects into Account

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Abstract: - Traditional insulating materials used in low-voltage machines cannot normally withstand steam because of the simultaneus presence of high temperature and humidity. In order to find a steam-resistant insulation system that includes magnet wire, groundwall and phase insulations and impregnating resin, accelerated aging tests were carried out applying small-scale models. Eight different insulation systems were constructed on these models, and seven different wire insulations were tested. The specimens were immersed in hot, pressurized water, which influenced the material instead of steam. Suitable materials for each part of the insulation system of a low-voltage, random-wound machine were found. Taking into account the thermal conductivities of each insulating material, the heat transfer of the machine was calculated for all the tested insulation systems.

Key-words: - AC Machines, Induction machine, Insulation, Magnet Wire, Water

1 Introduction

The importance of a proper insulation system of an electrical machine has been a relevant issue at least for the past hundred years. Insulating materials have been constantly developing, and partly because of their evolution, the variety of applications for electrical machines has become larger and larger. The properties of insulating materials have been a subject of extensive study, and their behaviour is well understood and reported [1]. The use of these materials in an electrical machine is also well known and documented [2]. The reasons for the behaviour and, in particular, the dielectric breakdown of solid insulating materials have been extensively discussed, for instance in [2, 3, 4, 5], but the world still lacks an inclusive explanation to the phenomenon.

Electrical machines are generally operated in convenient and clean environments such as in paper mills, the only external stress factor being the rise of the ambient temperature. For this purpose, insulating materials can be easily selected. By contrast, it is not common to operate motor windings in a very harsh environment including moisture, chemicals, gases or dirt. The tolerance of insulation systems in these difficult operating conditions has not been widely, if in some cases at all, reported. This paper discusses the issue of operating an electrical machine directly in steam, where both high temperature and humidity are present.

The steam resistance of insulating materials used in electrical machines is poorly reported in the literature. This is mainly due to the lack of applications in which steam resistance would be required. Steam resistance is often discussed with the generators operating in nuclear power plants. They may be exposed to steam during the loss of coolant accident (LOCA) or during the main steam line break (MSLB). Both situations may expose the generators to radiation as well. When LOCA or MSLB tolerance is required, it is common to use a sealed winding insulation system [2]. Furthermore, the cooling system of a turbo-generator used in nuclear power plants differs considerably from the conventional cooling constructions in size and also in cost, and therefore, the generator in a nuclear power plant can be considered a different kind of an application [6].

The application behind this paper is a combined heat and power (CHP) co-generation plant, which, by using bio fuel, delivers 4 MW of thermal and 1 MW of electrical power. The output power of the plant is rather small, and therefore, the plant cannot be cost-effective if constructed in a conventional fashion consisting of a turbine, an axle seal, a transmission and a traditional electrical generator. In such a construction, the axle seal between the turbine and the transmission is a weak link. It causes notable leaks in the process steam, and therefore, the plant needs a whole water supply unit to maintain the desired steam pressure. The water supply unit requires a lot of space and a complex automation system. A cost-effective alternative is a hermetically sealed turbo-generator consisting of a turbine and a low-voltage, medium-speed, solid-rotor induction machine (U = 690 V, n = 14000 rpm) driven by a frequency controller. The hermetically sealed structure does not require any axle seals, because the process steam is also used as the main cooling fluid of the generator, that is, the low-pressure process steam is flowing through the air-gap of the generator. Because there are no leaks, the expensive water supply unit can be eliminated. Furthermore, because the turbine, the generator and the main feeding pump are all mounted on the very same shaft, a transmission, which is also an expensive component, is not needed. The overall costs of the plant can thus be reduced to a reasonable level, yet no comparison is presented in this paper. The major problem in this kind of a plant is the construction of the generator, the insulation system of which must withstand steam, the temperature of which is 115 °C at all times. The steam-resistant insulation system is the price to pay for a cost-effective small-power CHP plant.

Steam seems to be one of the most aggressive substances to insulating materials used in low-voltage machines. It combines high moisture content and high temperature. In such an environment, insulating materials are prone to hydrolysis, which is a chemical reaction that combines the water molecules with the molecules of the insulating material. The prevailing temperature accelerates the reaction. From the insulating material point of view, the hydrolysis reaction is not of absorbing water, but rather of turning into a whole new material, which is no longer an insulator, or it is a very poor one. Hydrolysis can most easily occur in insulating materials including ester or imide functional groups. In the latter, the water molecule reacts with carbon and nitrogen by forming carboxyl acid [7]. Ester functional groups, in which the breaking bond is between carbon and oxygen, are more prone to hydrolysis (i.e. lower temperature is needed for the reaction to occur). Hydrolysis is a reaction that cannot be allowed in any circumstances. This can be achieved by proper material selection. An insulating material may also absorb water, which can cause some decrease in its dielectric properties. Water absorption is accelerated by the prevailing temperature. This is also a relevant issue, but, unlike hydrolysis, it can be tolerated.

This paper introduces a water-resistant insulation system to be used in a low-voltage electrical machine. The work is based on the results of two series of accelerated aging tests using commercially available insulation materials. In the first study, the operating temperature of steam was 90 ºC. Afterwards, further testing was needed, because the initial turn insulator was no longer commercially available. Furthermore, the second series was accomplished with a higher operating temperature, 115 ºC, and it also included testing the magnet wires separately. The effect of different insulation systems on the thermal state of the machine was evaluated using thermal resistance networks. It is shown that the thermal conductivity of the insulation system has a significant effect on the temperature rise of the machine, especially in the stator end-winding areas.

2 Structure of the insulation system

The generator studied in this work is designed to have random-wound stator windings to make the axial length of the generator as short as possible, which is beneficial from the mechanical point of view. The structure of the insulation system of a low-voltage, random-wound machine, presented in Fig. 1, consists of a turn insulation, groundwall insulation, phase insulation and impregnating resin. One must keep in mind that every single part of the insulation system must withstand steam. This is because the cooling steam can be assumed to be able to penetrate everywhere in the structure, even though the impregnating resin should basically cover also all other parts of the insulation system.

Besides the above-mentioned parts, there are many other components in the stator that also have to be insulated. These are the connection wires from one coil to another, from the coil to the feed-through connectors in the frame among with the cable shoes and other connection structures.

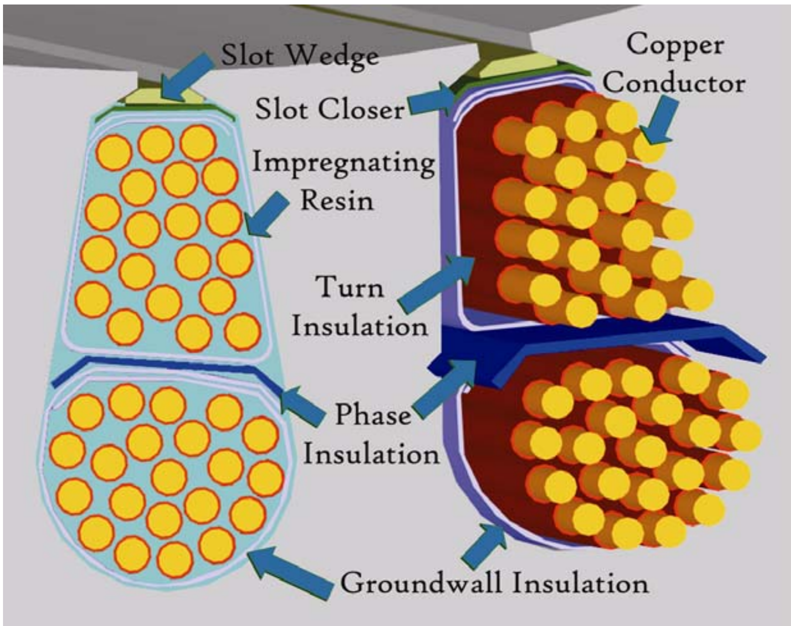

Fig. 1. Structure of the stator insulation system in the stator of a low-voltage, random-wound machine.

Even in low-voltage machines, partial discharges may be present, when the machine is driven by a frequency converter, which is the case in the generator studied. Partial discharges are due to the fast rise times of voltage pulses, which cause reflections and uneven voltage distribution in the stator windings. There are various ways to prevent partial discharges from breaking the machine (see e.g. [8]). The problem can be solved for instance by installing a low-pass filter between the generator and the frequency converter. This will slow down the pulses and thereby prevent partial discharges. Furthermore, the low-pass filter reduces especially solid-rotor losses in the generator [9].

2.1 Groundwall Insulation

The most important part of the insulation system is the groundwall insulation. It alone should be able to completely withstand the electrical stress between the stator voltage and ground and prevent short-circuits between the conductors and the stator core. The phase insulation prevents short-circuits between different phases. Both the groundwall and phase insulations as well as the slot closer are usually made of the same material.

Normally, the groundwall insulation consists of thin sheets of synthetic polymers, such as Nomex aramid paper, Kapton polyimide film or Mylar PET (polyethylene-terephtalate) film (all trademarks of DuPont). Also polyester films can be used. Studies made by Campbell on the hydrolytic degradation of Kapton polyimide [7, 10] show that Kapton does not survive even a single week in the conditions involving 100 % relative humidity and a temperature of 100 ºC. Mylar and polyester films contain ester functional groups, which are prone to hydrolysis. Nomex is in this respect not as vulnerable as other materials mentioned.

2.2 Turn Insulation

The purpose of the turn insulation is to prevent short-circuits between different turns and guide the current through every turn of the coil. The dielectric strength required for this is usually not very high. The turn insulation must withstand high mechanical stress during the manufacturing process of the winding; they are stretched and bent, and come constantly in contact with sharp edges.

Turn insulation is typically made of some polyester-based material. A common insulation solution is to use a structure consisting of a polyester-imide base coat and a polyamide-imide overcoat. Both of these layers contain imide functional groups, which cannot withstand steam. Kapton polyimide can also be used as a turn insulation in special applications including high operating temperatures, such as in traction motors, where its unique properties cancel out its very high price.

Turn insulation can, in rare cases, be also made of different fluoropolymers, such as FEP (fluorinated ethylene-propylene) and PTFE (polytetrafluoroethylene). They do not contain functional groups prone to hydrolysis and, furthermore, they do not absorb water, which is very promising from the steam resistance point of view.

When water is present, wires insulated with PVC (polyvinyl chloride) may come into consideration. PVC forms a very thick insulation layer, which has to be taken into account in machine design. PVC is commonly used in submersible pumps.

In many applications, where the steam resistivity in high temperatures is required, a PEEK (polyether-etherketone) polymer is used. PEEK can resist hydrolysis in temperatures up to 250 ºC [1]. PEEK has been commercially available for turn insulation for some time, but PEEK-insulated magnet wires are not available as bulk products. Therefore, the price of PEEK is very high and consequently, the variety of applications is quite limited.

2.3 Impregnating resin

The impregnating resin, although usually having appropriate dielectric properties, is used for mechanical rather than electrical reasons in low-voltage machines. The purpose of the resin is to fill all gaps and voids in the stator slot. It also provides mechanical support and shield in the end-windings. Because of the presence of steam, the latter is a very important issue. The magnetic field created by the stator currents produces an oscillating force, the frequency of which is twice the frequency of the stator current as presented by Calvert [11]. This oscillation can bend, twist or, in the worst case, crack the coils, if the stator slot is not completely filled with resin. The motion of coils in the slot can tear the groundwall insulation and ultimately cause a failure. Therefore, it is very important that the steam cannot dissolve the resin from the slot.

When choosing the right impregnating resin, one must usually make the decision between epoxy and polyester. In typical applications, polyesters are used because of their low price and ease of handling. Polyesters can tolerate high temperatures, and they have good mechanical properties. In harsher environments, epoxies are favoured because of their better characteristics. In some special applications involving very high temperatures, silicone resins can be used. Their mechanical properties, however, are quite poor. Also polyester-imide resins can be used; they are derivatives of polyester resins with slightly better general characteristics and somewhat higher price.

3 Methods of Analysis

The problem of the steam resistivity of different insulation structures was tackled experimentally: accelerated aging tests were made for a set of selected insulation structures. The idea of above-mentioned accelerated aging tests is based on the work of Dakin, who in 1948 explained that the thermal deterioration in insulation is due to changes in the chemical structure of the organic material [12]. According to Dakin, the relationship between the lifetime, L, of the insulation system and the prevailing temperature, T, is

$$L = Ae^{\frac{B}{T}}, \tag{1}$$

where A and B are constants. Equation (1) is better known as the Arrhenius chemical deterioration rate equation and it can be approximated as follows: if the operating temperature of the machine rises by 10 ºC, the time to failure decreases by 50 % [2].

The tests for insulation systems were carried out using small-scale models, known as motorettes. A total of eight motorettes were built according to the IEEE standard test procedure [13], and they were tested as two individual test series. The magnet wires were tested simultaneously with the insulation systems in the second series of testing. The motorettes and magnet wires were attached to a support structure, which was welded to the lid of the pressure vessel. The wires were tested as approximately 30-cm-long pieces. There were two different specimen of each wire: one was the wire as such, undamaged, and the other was mechanically damaged in advance. The specimens were cut with a knife to imitate the possible damages caused by the manufacturing process of the machine. During the manufacturing process of a random-wound electrical machine the magnet wires are stretched and bent or otherwise roughly handled, and they come constantly in contact with sharp edges, as mentioned above.

The specimens were immersed in hot, pressurized water for eight days. The temperature of water was in the first testing series 130 ºC and in the second series 150 ºC. The time and temperature were chosen based on the interpretation of Eq. (1) and instructions in [13]. According to [13], the specimens should survive 32 days in the temperature of 15 ºC higher than their standardized temperature class. In this case, the temperature classes can be replaced with the temperature of the process steam, the maximum value of which is designed to be 115 ºC. Therefore, the specimens should withstand 32 days in the temperature of 130 ºC. According to the interpretation of Eq. (1), the specimens intended to be used in 115 ºC should tolerate the temperature of 140 ºC for 16 days and 150 ºC for eight days.

After the water exposure, the specimens were attached to a vibrating bench, which imitates the vibrations caused by the alternative current in actual machine. According to [13], the amplitude of the vibration was set to 0.1 mm and the frequency to 50 Hz. The vibration test was performed only with the first testing series having the temperature of 130 ºC. For the second testing series, the test was omitted, because it was found to have only a slight effect on the results. The test did not affect the specimens that survived the water exposure.

After each test and two times during the water exposure, the motorettes were analyzed. First, the motorettes were thoroughly investigated in order to find any possible cracks, breaks or places where the resin was missing. The groundwall insulation was tested by applying a 2700 V DC voltage (maximum with our equipment) to both coils of the motorette, while the framework was kept at ground potential. The phase insulation was tested by applying the same voltage to one coil while keeping the other grounded. If a fault current as high as several mA was observed in the circuit, the insulation was considered faulty. With our equipment, the failure was detected, when the current was high enough to trigger the safety mechanism of the voltage supply, which then turned the power off. Also the insulation resistance was measured. The resin was analyzed by bare eye inspection. The motorettes were thoroughly investigated for any cracks, breaks or places where the resin was missing.

The wire specimens were analyzed with a microscope after the tests. The analysis focused on two main questions: had the undamaged wire suffered any damage during the exposure and had the damages made beforehand expanded?

Although the conditions inside the generator involved steam, the specimens were tested in high-temperature water under pressure. This may seem to be somewhat misleading, as water in liquid form constitutes a different medium than 100 % relative humidity, which may cause the insulating materials to behave in slightly different ways. Nonetheless, the molecules of water are the same in both cases and, therefore, the chemical reaction, which is supposed to cause the failure of insulation, is the same. Furthermore, already in the early work by Halpern, it was shown that when the steam resistivity of the insulation is studied, the high temperature water under pressure gives results similar to the steam effect [14]. Again it should be noted that the application studied here is a low-voltage generator, the insulation system of which is highly unlikely to suffer a failure caused by partial discharges and, thereby, electrical treeing. Instead, the insulation system can be expected to suffer from chemical aging caused by hydrolysis. Eventually, this would lead to breakdown, which is more of thermal than electrical nature.

In order to study the effect of the thermal properties of the insulation systems on the temperatures in different parts of the 1 MW machine, a thermal analysis based on a thermal resistance network was performed. In the thermal network model, the heat transfer both in axial and radial directions was taken into account. The convection coefficients and the losses caused by the cooling fluid friction were calculated by analytical equations. The electromagnetic losses of the machine were calculated applying the two-dimensional finite element analysis. A special cooling matrix was used to model the heating of the cooling steam [15]. The main equations and the structure of the thermal model are found in [16, 17]. The reason why thermal analysis was included in this study was the idea that the thermal properties and particularly the thermal conductivity of the insulation system could eventually decide the temperature rise of the stator windings. This can be explained as follows: In the windings placed in the stator slots, the thermal conductivity λ in the axial direction almost corresponds to the copper conductivity, c. 400 W/mºC. Because of the presence of different insulation layers, the thermal conductivity in the radial direction is notably lower, the reported values of which are below 1 W/mºC [18]. The equivalent thermal conductivity λ_{eq} of the winding consisting of copper wires and different insulation layers in the radial direction can be calculated as [19]

$$\lambda_{\mathrm{eq}} = \frac{\sum_{i=1}^{N} d_i}{\sum_{i=1}^{N} \frac{d_i}{\lambda_i}}, \tag{2}$$

where d_i is the thickness and λ_i is the thermal conductivity of the i^{th} insulation layer, respectively. Because of the significant difference in the thermal conductivity in the axial and radial directions, the heat generated by the coil losses is transferred from the stator stack area to the end-windings, where the heat is eventually removed by thermal convection to the cooling steam. However, due to the high thermal resistance in the radial direction, the temperature difference between the cooling fluid and the end-winding is large regardless of the effectiveness of the convective heat transfer of the end-winding. This is the reason why the maximum temperature of electrical machines is usually found in the end-winding areas. The thermal analysis of the generator was performed at the point of 20 per cent overloading; in other words, the output power of the generator was 1.2 MW.

4 Tested structures

The structures of the insulation systems used in tests are listed in Table 1. Most of the structures were built based on Nomex aramid paper, since it seemed to be the only synthetic groundwall insulation material that could survive the tests. Also polyester film was tested as a groundwall insulation. Kapton polyimide was tested as a turn insulation. The motorettes in the first testing series were wound with Kapton wire having a thin FEP layer on top. The motorettes in the second testing series were wound with different wires. Single-component polyester resin was tested both separately and covered with two-component epoxy potting resin, which was supposed to give a proper shield in the end-winding area. Two-component epoxy potting resin was selected because of its very high thermal conductivity. Also single- and two-component epoxy impregnating resins and polyester-imide resin were tested. The equivalent thermal conductivities of different insulation systems were calculated with Eq. (2). The thicknesses of the insulation layers were 0.1 mm for the turn insulation, 0.5 mm for the groundwall insulation, 0.35 mm for the impregnating resin and 1.5 mm for the copper conductor. The thermal conductivities of the insulating materials considered are listed in Table 2.

Table 2. Thermal conductivities of the insulating materials analyzed.

Material	Thermal conductivity [W/mK]
Polyester-imide-polyamide-imide	0.215 *
FEP	0.195
PTFE	0.245
PEEK	0.25
Polyolefin	0.036
Silicone	0.22
Nomex	0.157
Kapton	0.2
Polyester resin	0.076
Polyester imide resin	0.17
1-component epoxy resin	0.23
2-component epoxy resin	0.2
2-component epoxy potting resin	01.01.07

* It is assumed that both layers are of the same thickness. Thermal conductivity is the average of polyester-imide (0.17 W/mK) and polyamide-imide (0.26 W/mK).

Table 1. Insulation systems used in the tests. The rated temperature column separates two different testing series. In the motorette number 7, the upper coil was wound with FEP-insulated wire and the lower coil with polyolefin wire.

	Turn insulation	Groundwall insulation	Impregnating resin	T [°C]	Effective thermal conductivies [W/mK]
1	Kapton	Nomex	unsaturated polyester resin	90	0.2954
2	Kapton	Nomex	unsaturated polyester resin / two-component epoxy potting resin	90	0.3251
3	Kapton	Nomex	single-component epoxy resin	90	0.4702
4	Kapton	Polyester	two-component epoxy resin	90	0.4716
5	Polyester-imide and polyamide-imide	Nomex	single-component epoxy resin	115	0.4715
6	Polyester-imide and polyamide-imide	Nomex	single-component polyester-imide resin	115	0.4273
7	FEP / Polyolefin	Nomex	single-component epoxy resin	115	0.4702 / 0.3272 *
8	Silicone	Nomex	single-component epoxy resin	115	0.4744

* For FEP and polyolefin respectively

The insulation systems in the motorettes were built similarly as the one in Fig. 1 with the exception of the phase insulation not being used inside the slot, and a slot closer not being used at all. They had no insulating function in this case and were not needed from the manufacturing point of view either. The slot wedges used in the motorettes were made of glass fibre.

The wires used in tests are listed in Table 3. Not all the wires selected are suitable as magnet wires. With silicone and polyolefin wire insulation, the copper filling factor of the slot would be too low. These wires can be used for the connections from the winding to the feed-through parts. However, in order to see how they act with the impregnating resin, they were used as magnet wires in the motorettes 7 and 8, respectively.

Table 3. Winding wires used in tests.

Wire insulation	Purpose of wire
Polyester-imide + polyamide-imide	winding
Kapton polyimide	winding
PVC	winding
Silicone	connections
Cross-linked polyolefin	connections
FEP	winding/connections
PTFE	winding/connections

5 Results and discussion

It was found that Nomex aramid paper survived the tests in both temperatures, even when the resin and turn insulation failed. Nomex absorbs some water, which causes a decrease in its dielectric strength. This was indicated by a slight increase in the fault current as the time of exposure went on. The thickness of Nomex layer in the insulation system should thus be oversized. A Nomex-layer of twice the thickness set by the operating voltage is adequate for the application. Nevertheless, Nomex survived all the voltage tests. The insulation resistance was in all cases too high to be measured; over 1000 MΩ.

The polyester film, on the other hand, suffered from severe embrittlement and lost its dielectric strength when exposed to water at the temperature of 130 ºC. It seemed that the polyester film had been boiled away from the slot. Some of the reaction results were seen in the form of foam on the coil in the end-winding area. Due to the failure of the polyester film, the motorette number 4 did not survive the voltage test, although there seemed to be no damage in the resin layer. The insulation resistance was measured to be approximately 0.7 MΩ from the conductor to the motorette frame.

Both the epoxy impregnating resins held their structures very well at 130 ºC. The single-component epoxy resin survived also at 150 ºC. The single-component epoxy resin was able to form a thicker layer in the end-winding area than the two-component one. The end-winding area of the motorette number 5 after testing at 150 ºC is illustrated in Fig. 2. In the figure, it can be observed that the impregnation is still very thorough and no damaged spots can be found, although the resin has come loose from the motorette frame, which is an irrelevant issue in the case of the resin being a part of the insulation system.

Fig. 2. Motorette number 5 after the exposure to water at 150 ºC. Note that impregnation is still very thorough.

In Fig. 2, there are many bright spots on the coil. These spots are bare copper, from which the turn insulation has vanished. On these spots, there was a seemingly undamaged resin layer still covering the coil. Similar disintegration of the turn insulation took place also with the motorette number 6, but in that motorette also the resin had suffered notable damages.

The polyester resin came loose from the magnet wire widely in the end-winding area. It seemed that more resin was missing than was still attached to the winding. Also the effort to cover such a motorette with epoxy potting resin failed badly. The epoxy potting resin suffered severe damage during the exposure to water at 130 ºC and even more after the vibration test. It had plenty of cracks, through which the magnet wire could be seen, as can be observed in Fig. 3. Obviously, potting resin is designed to cover surfaces that stay still. Its promised ability to operate as a cover or shield in the end-winding area can be questioned. However, one must bear in mind that the vibration test was carried out after the resin had been immersed in hot water and had already been damaged. The exposure to water had apparently weakened the mechanical properties throughout the resin, not just in the cracked spots.

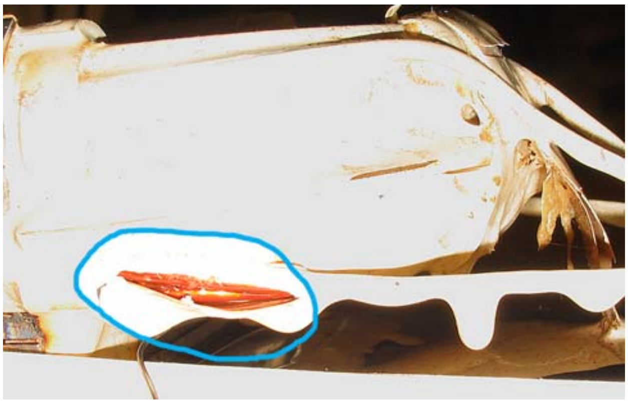

Fig. 3. Motorette number 2 after the tests. Note a huge crack.

The polyester-imide resin was tested only at 150 ºC. Some of the resin was still attached to the coil, but notable amount of it had been dissolved away. When compared with the polyester resin, the polyester-imide resin seemed to tolerate the hot water notably better. It was tested at higher temperature, but still suffered less damage. Yet, its competitiveness in this very occasion is lower than that of epoxy resins.

Kapton polyimide failed as turn insulation at 130 ºC in the motorettes 1-4. At many spots, it came loose from the copper conductor. There were also spots where the wrapped insulation structure was damaged and had totally lost its dielectric properties. At these spots, Kapton was still attached to the magnet wire, but could not cover it completely. These spots were found even in such places where there was an apparently undamaged resin layer on top of the wire. Such situations occurred with the motorettes 3 and 4.

On the other hand, the Kapton-insulated magnet wire survived the test at 150 ºC, when tested alone and undamaged. The answer to this contradiction lies in the thin FEP layer on top of Kapton. When the wire was tested alone, the FEP layer protected Kapton and the wire suffered no damage at all. Instead, when used as a turn insulation as a part of an insulation system, the FEP layer was probably damaged due to the high adhesive force of the epoxy resin. The resin tore the FEP layer, and water could get in contact with Kapton. This happened also to the wire specimen, which was intentionally damaged in advance, as illustrated in Fig. 4.

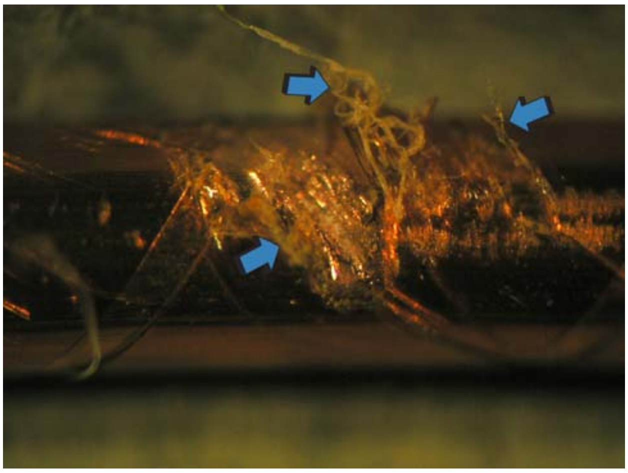

Fig. 4. Kapton polyimide-insulated wire from the point of a cut made in advance. Oddly-shaped strings marked with arrows are Kapton that has come off from the wire.

The magnet wire tests at 150 ºC indicated clearly that polyester-imide- and polyamide-imide-insulated magnet wire and PVC-insulated wire do not withstand steam. In Fig. 5, there is a picture of the former and in Fig. 6 of the latter, both at the points of no cut after the exposure to hot, pressurized water. The tests also proved that both fluoropolymers, FEP and PTFE, can withstand steam, as can silicone and polyolefin. It seemed that water had no effect on the fluoropolymers. Meanwhile, silicone and polyolefin had absorbed water during the exposure, especially the former, the swelling of which had caused cracks in the resin layer in the motorette 8.

Fig. 5. Polyester-imide- and polyamide-imide-insulated wire after the exposure to hot, pressurized water. There is only a slight attachment between the insulation and the copper conductor. From most parts, the insulation has already decomposed.

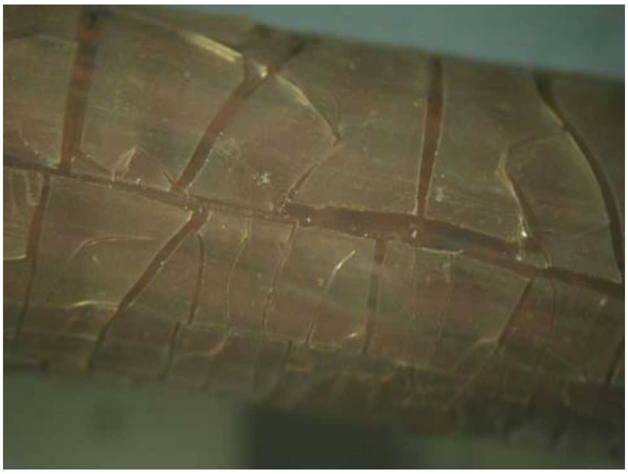

Fig. 6. PVC-insulated wire after the hot, pressurized water exposure. The surface of the insulation has suffered from severe cracking.

According to the tests, the steam-resistant insulation system can be built using fluoropolymer-insulated magnet wire, Nomex aramid paper and single-component epoxy impregnating resin. The connection wires in studied generator can be insulated either with fluoropolymers, polyolefin or silicone. The slot closers should be made of Nomex, and the slot wedges can be made of glass fibre, which did not show any signs of failure during the tests. Among with the materials tested, also PEEK should be noted here. If available, it can be used for the turn insulation.

The results from the thermal analysis of the machine with different insulation systems at the output power of 1.2 MW are presented in Table 4. It has to be noticed here that the temperatures at the 20 per cent overloading are approximately 15-20 ºC higher than it would be the case in the nominal operation point, which is 1 MW.

Table 4. Calculated temperatures in the coil end-windings with different insulation systems.

Insulation system (Table 1)	D-end end-winding temperature [°C]	ND-end end-winding temperature [°C]
1	178.5	177.5
2	173.7	172.4
3	137.2	134.6
4	140.8	138.4
5	137.1	134.4
6	145.3	143.1
7a	137.3	134.6
7b	168.8	167.6
8	136.6	133.9

As it is seen in Table 4, the thermal conductivity of the insulation system has a significant effect on the end-winding temperatures. The highest end-winding temperatures are found when at least one part of the insulation suffers from poor thermal conductivity. In the systems 1 and 2, the weakest link is the impregnating resin, while in the system 7b, it is the turn insulation. When a steam-resistant insulation system is required, the lowest end-winding temperatures are obtained with an insulation system consisting of Nomex aramid paper, single-component epoxy resin and fluoropolymer- or silicone-insulated magnet wires. PEEK magnet wire was not included in the thermal analysis, but because its thermal conductivity is higher than that of silicone, the end-winding temperatures would be somewhat lower compared with the temperatures obtained with the insulation system 8.

6 Conclusions

Accelerated aging tests were carried out for various insulation systems and different magnet wires in hot, pressurized water. The study was made in order to find a steam-resistant insulation system for the stator of a low-voltage, random-wound 1 MW, 14000 rpm induction generator.

According to the tests, the steam-resistant insulation system can be built using Nomex aramid paper for groundwall and phase insulation and for the slot closer. The turn insulation should be made of either fluoropolymers or PEEK. The insulation of the connection wires should consist of the insulation materials proposed above for the magnet wires, or of silicone or polyolefin. For impregnating resin, single-component epoxy is proposed. Glass fibre can be used for slot wedges. The steam-resistant insulation system can be constructed with materials commercially available. However, the thickness of the insulation and issues related to the manufacturing must be re-evaluated. For example, wires coated with fluoropolymers may not withstand the mechanical stresses of the winding process. PEEK-insulated wires can be handled as usual wires.

In order to withstand steam, or in fact nearly any environment one can possibly imagine, all the components of the insulation system have to be resistant to it, not only the outermost one. Most likely, water cannot penetrate the resin layer, but finds its way for instance through some small pores that always exist in the resin layer. These pores may be created by inadequate impregnation, but also because of the heat expansion of the resin.

The tests showed how an aggressive element hot water is. The materials that can resist even very toxic acids suffer severe damage when exposed to hot water. Hence, considering different solvents and the resistance of synthetic insulating materials to them, of them all, it is surprisingly water, the most essential prerequisite to life, which seems to be the deadliest.

The effect of the thermal conductivity of the insulation system on the temperature rise of the end-windings was studied by applying thermal resistance networks. It was shown that the end-winding temperatures of the machine are strongly dependent on the thermal properties of the insulation system.

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