PRODUCTION ENHANCEMENT THROUGH USING A CONTINUOUS SYSTEM OF WINDING ELECTRIC MACHINES

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The article is focused on the practical test of stator coil isolation by a continuous winding system. The winding system has two types. Discontinuous winding requires precise manual winding of the material. Discontinuous winding is time consuming. The use of the winding machine is limited by a maximum voltage of 11 kV. With continuous winding, the machine winding is accurate, the winding time is lower and the winding machine is used for a voltage greater than 11 kV. The disadvantage is the greater number of multi-stage corrosion protection strips that are pressed into the coil.

The next part deals with the time sequence in operations and production tests with coils Un = 6 kV and Un = 11 kV.

The result of this study is to make the production of stator coils more efficient by means of a machine winding device and suitable determination of types of stator coils.

KEYWORDS
insulation, stator coil, voltage, operating tests, winding

1 INTRODUCTION

Insulation systems of electric machines can be divided, in terms of materials used and corresponding impregnation, into the RR (resin-rich on the basis of pre-impregnated tapes) type, and the VPI (vacuum pressure impregnation for materials on the basis of absorbent mica tapes) type.

The RR insulation systems can then be sub-divided, in terms of the way of insulating and curing, as follows:

- Continuous (the running insulation with one type of tape), curing in the entire length;
- Continuous (the running insulation with one type of tape), curing of the straight section;
- Discontinuous (the straight section and the front sections insulated with different tapes), curing of the straight section.

The VPI insulation system is applied in two ways: either as the overall impregnation when the whole stator is insulated after having been wound, or by impregnating individual bars.

The limit is given by the size of the machine. Small and medium machines are impregnated as the whole, in large machines, individual bars are then impregnated.

2 INSULATION SYSTEM SELECTION

Comparison of the discontinuous system RR with the continuous system having straight section cured their advantages and disadvantages. The advantage of the VPI system consists in a very good binding between the winding and the magnetic circuit, and almost identical thermal and electric properties of the insulation of the groove part and front sections.

Disadvantage then consists in high investment costs, high energy consumption, as well as in the difficult reparability of the stator in case of the overall impregnation. Advantage of the continuous insulation system RR with the continuous curing consists in high dielectric strength in the entire length; almost identical thermal and electric properties of the groove part and front sections, high thermal conductivity even in front sections, low energy consumption and the reparability of winding. Disadvantage consists in the need for costly individually manufactured fixtures for curing the insulation of front sections.

The system RR of continuous insulation with a cured straight section has high dielectric strength in the grooved part, low energy consumption and needs simple fixtures. The winding is also easily reparable. Disadvantage consists in low thermal conductivity of the winding of front sections.

The system RR of discontinuous insulation has high dielectric strength in the grooved part, low energy consumption and needs simple fixtures. The winding is easily reparable. Disadvantage consists in low thermal conductivity of the winding of front sections and higher labour input in insulating.

The discontinuous insulation system applied to the coil or the bar, respectively, consists in wrapping of the straight section of the prebaked coil with the insulation foil, which is then cured in the press under a prescribed pressure and at the prescribed temperature. Once the protection against corona at the output from the groove (a semi-conductive and conductive varnish or, eventually, at the same time, the conductive tape with the pressed foil) is completed, insulation of the coil front sections with the tape is performed always overlapped over the straight section.

The use of the foil for insulating the straight section of the coil ensures the homogeneity of components it contains (glass fibre fabric or PET, mica, resin) and, thus, the identical properties along the entire length of the cured straight section. The wrapping process runs relatively fast. However, a sensitive location is formed at the end of the cured straight section. Even it is then wrapped with the insulation of the front sections, this location represents, with respect to inter-operation tests, as well as after having been mounted into the stator, the danger of discharges occurrence that can gradually degrade the insulation over the time.

For this reason, it is inevitable to strictly observe the so-called minimum distances in the front section of the alternating currents space (the conductive part of the protection against corona - the discontinuous transition, bare grounded metal - the discontinuous transition). It follows from the above that the straight section of coils produced this way must have the length of the cured straight section always by a certain minimum distance larger than the stator iron length.

On the other hand, as this way of insulating in the production of coils allows first wrapping and curing the straight section only (in the form of the so-called "hairpin") and then forming the coil in the coil-spreading machine, the so-called "multiple press" can preferably be used for curing the straight section (limitation for the use of this press is given by the straight section length and the overall length of the hairpin). However, the discontinuous insulation system can only be used for the maximum voltage of the electric machine U_n = 11 kV. The continuous insulation system with the cured straight section consists in the running insulation of the whole coil all at once with one type of the insulation tape.

The curing of the straight section, including creation of the protection against corona, is done the same way as in the discontinuous system. As no discontinuous transition occurs in this way and, thus, the same distances need not to be observed like in the discontinuous system, the coil is shorter in its axial direction. The shortening of coils means simultaneously that the losses in the winding are reduced. The continuous insulation system can also be used for higher machine voltages than U_n = 11 kV. However, for these higher voltages there is the need of solving the problem with pressing the tapes for multistage protection against corona even in locations with the bend into the front section as it needs more complex fixtures for pressing. The disadvantage of this system consists in the impossibility of using the multiple press for curing the main insulation as coils must be formed before their insulation.

3 ANALYSIS OF PRODUCED COILS IN RELATION TO APPLICABILITY AUTOMATIC WRAPPING MACHINES

Half-baked coil was isolated in company Micamation wrappers over the straight part, but due to the relatively small space between the straight portions (coil opening) is winding head reaches only 70 mm in the front. From this point you should no longer have to be manually isolated coil, which in comparison with discontinuous recovery process yielded the desired effect savings in insulation faces and the connection point of the tape would lie adjacent the end of the straight part.

The parameters of this coil is why it is taken as determinative in deciding on the effective respectively. Inefficient facilities automatic wrappers. For the possibility of using the wrapping head, the dimensions of the coil below are important: the cross-section, the space between straight sections, the straight section length, and the distance between centres of the coil eyes.

It were chosen the last 40 different shapes of coils that have been in our society completely isolated and compared with the requirements for the wrapping head according to technical documentation supplied by Micamation. All the coils complied with the requirement for the straight section length and the distance between centres of the coil eyes. Thus, values of the cross-section and the space between straight sections of the coil were used for the analysis.

Winding head MZ-961-S requires these values insulated coil:

- Maximum length of the diagonal of the insulated coil (coil diagonal)……….65 mm;
- Space between straight sections (coil opening)………………………230 – 1200 mm [Kothari, Nagrath,2006]

From the sample 40 of coils under evaluation, the automatic wrapping machine MI 155 with the wrapping head MZ-961-S could not be used for 7 orders and in 8 orders its use would not bring any positive effect as it would, in addition to the straight section, wrap just a negligible part of the coil front section. The machine is efficient for 25 coils, which accounts for 63% of the production.

4 AUTOMATIC WRAPPING MACHINE RELATION TO OTHER PRODUCTION EQUIPMENT

The decision on acquiring the automatic wrapping machine must be, among others, based on the overall conception of the production equipment that will be used for the complete production of coils.

Otherwise, we can get into the situation when the coils wrapped by the automatic wrapping machine will cumulate and "wait" until the next production device is available. From this point of view, the application of the automatic wrapping head would lose its importance.

Assuming that prebaking of coils will, with the coil shop equipment, always be done on 2 presses at a time, and 4 coils sides will be prebaked in each press at a time, and the same will be done in another couple of presses for curing the main insulation, the time requirements for individual operations will be as shown in Fig. 1 and Fig 2. The times of individual operations depend on the coil size and cross-section, the number of threads in the coil, and the number of wires in the thread.

However, the scatter of these values is relatively low, so that it can be stated that the longest time in production of coils using the automatic wrapping machine, while all other operations are being performed simultaneously, will be needed for the very wrapping by the wrapping machine and for coils forming.

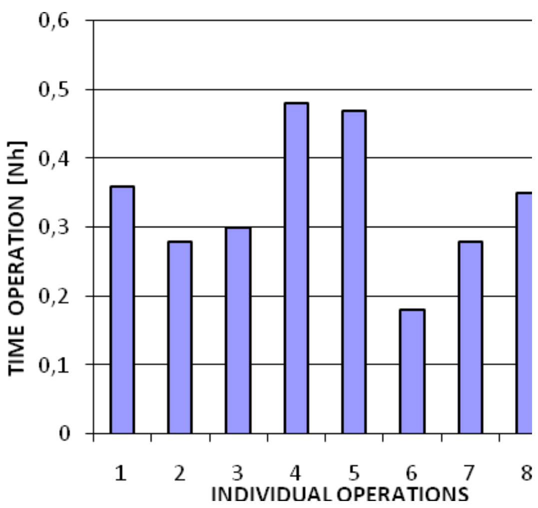

Figure 1. Parallel operations in the production of coil 6 kV

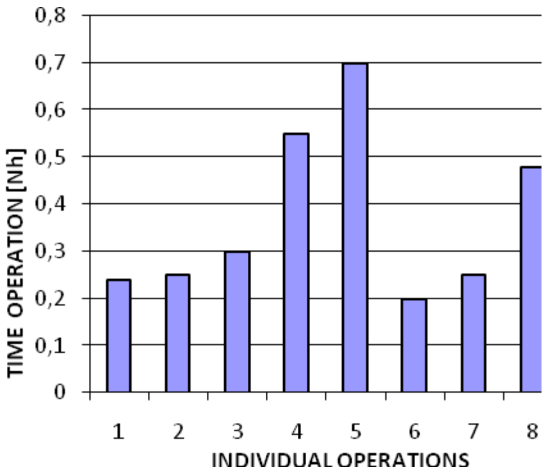

Figure 2. Parallel operations in the production of coil 11 kV

Legend of operations:
1 – Hairpin
2 – Manipulation - Prebaking
3 – Prebaking
4 – Forming
5 – Wrapping machine insulating
6 – Front section manual finish insulating
7 – Manipulation – Main insulation curing
8 – Main insulation curing

Only in the case when the coil dimensions do not allow curing 4 coils sides in one press at a time, the double time will be needed here and this operation will be the weakest point in the coils production from the time continuity point of view (the longest is for coils U_n = 10 – 11 kV where the main insulation curing time at a temperature is by 50% longer than for coils U_n = 6 kV).

5 AUTOMATIC WRAPPING

Tests on coils insulated by continuous system automatic wrapping machine MI 155.
For coils insulated by the automatic wrapping machine MI 155, the quality of laying the tape was monitored (overlapping, tape tightening) and then the voltage tests were performed (uncured insulation).
The values found for breakdown voltages were $U_{break.}$ = 35,4 kV for 12 positions tape and $U_{break.}$ = 54,5 kV for 20 positions which averages to 17,7 kV/mm as recalculated per the unit dielectric strength. Arrangement of protection against discharge for U_n = 11 kV.

Tests on mandrels
The insulation tape was wrapped manually on the Fe mandrel sized 26 x 8 – 600 mm length L_i = 550 mm – Fig. 3 . A conductive electrode (tape 04 ESR 22 AA SK 400, 1 x s ½, L_{sh} = 100 mm) was created in the centre of the mandrel.
The protection against discharges was done by means of the semi-conductive tape (pos.3, tape EGSB 2969, 1 x s½, L_pr = 120 mm for U_n = 6 kV and L_{pr} = 145 mm for U_n = 11 kV) [Green,2012]. The conductive and semi-conductive tapes overlapped each other in the length of 20 mm for U_n = 6 kV and 25 mm for U_n = 11 kV.

Pos. 1 ....the Fe mandrel
Pos. 2 ....the insulation tape Calmica 70 0867 (0,16x20)
Pos. 3 .... the tape EGSB 2969 (0,15x20)
Pos. 4 .... the tape 04 ESR 22 AA SK 400 (0,1x30)

Insulated mandrel:

- Constant values ....w = 8 mm; h = 26 mm; L_i = 550 mm; L_{sh} = 100 mm
- Variable values .... t, L_{pr} conductive and semi-conductive tapes overlap

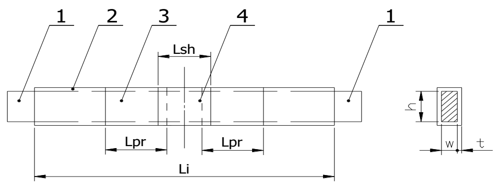

Figure 3. Composition of the mandrel

Values found for the breakdown voltage of mandrels $U_{break.}$ (kV), calculated mean value of the breakdown voltage U_{center} (kV), and the sample standard deviation σ (kV) Tab. 1.

	$U_{break.}$(kV) – uncured insulation Calmica 70 0867 – 0,16 x 20			U_{center} (kV)	σ (kV)
U_n = 6 kV 4 x ½ př. t = 1,3 mm	23,7	24,5	26,6	24,9	2,21
U_n = 11 kV 6 x ½ př. t = 1,9 mm	35,2	37,8	38,6	37,2	2,88

Table 1. Calculation of the mean value of the breakdown voltage $U_{stř.}$ and the standard selective variance σ

6 TEST ON COILS INSULATED MANUALLY IN CONTINUOUS SYSTEM

Coils for U_n = 6 kV
5 coils were produced for the voltage level of U_n = 6 kV, continuous insulation system, manual wrapping. Front sections insulated 4 x s½ (8 positions), coil straight section – 13 tape position (compressibility after curing 22%). Straight section curing – 1 hour at a temperature 165°C [Green,2012].
Test arrangement according to fig. 3 with the following parameters: L_i = 750 mm, L_{pr} = 210 mm (tape EGSB 2969 0,15x20), L_{sh} = 160 mm (tape 215.55 0,1 x 20). Protection tapes wrapped after the main insulation pressing; their mutual overlap – 30 mm.
Values found for the breakdown voltage U break. (kV), calculated mean value of the breakdown voltage U_{center} (kV), and the unit dielectric strength E (kV/mm) Tab. 2

	U break. (kV) – straight coil part molded insulation Calmica 70 0867			U center (kV)	E (kV/mm)
U_n = 6 kV t = 1,6 mm	64,4	61,2	60,5	62,0	38,8

Table 2. Measured values, mean breakdown voltage and unit strength

Test arrangement according to fig. 3 with the following parameters: L_{pr} = 100 mm (tape EGSB 2969 0, 15 x 20), L_{sh} = 140 mm (tape 215.55 0,1 x 20) Mutual overlap of tapes for protection against corona 20 mm.

Values found for the breakdown voltage U break. (kV), calculated mean value of the breakdown voltage U center (kV), and the unit dielectric strength E (kV/mm) Tab. 3

	U break. (kV) – face uncured insulation Calmica 70 0867			U center (kV)	E (kV/mm)
U_n = 6 kV t = 1,3 mm	24,2	25,8	27,3	25,8	19,8

Table 3. Measured values, mean breakdown voltage and unit strength

After the straight section pressing, the front sections of the coil were wrapped with the shrink lace and the coil was put into the oven for 10 hours at the temperature of 130°C. See test arrangement uncured forehead.

Values found for the breakdown voltage U break. (kV), calculated mean value of the breakdown voltage U center (kV), and the unit dielectric strength E (kV/mm) Tab. 4

	U break. (kV) – face cured insulation Calmica 70 0867			U center (kV)	E (kV/mm)
U_n = 6 kV t = 1,3 mm	27,3	27,4	25,1	26,6	20,5

Table 4. Measured values, mean breakdown voltage and unit strength

The measurement was carried out in the arrangement according to the applicable standard; the length of the measurement electrode was 550 mm, shading strips 50 mm, the gap 3 mm.

Loss factor values measured at 20°C; graphics course Fig. 4

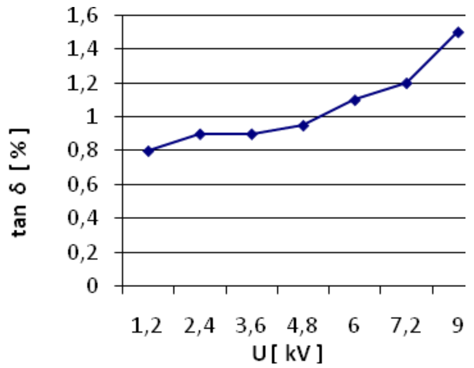

Figure 4. Process tan δ loss factor – insulation Calmica 70 0867; t = 1,6 mm

Coils for U_n = 11 kV

Five coils were produced for the voltage level of U_n = 11 kV, continuous insulation system, manual wrapping. Front sections insulated 6 x s ½ (12 positions), coil straight section – 22 tape position (22% compressibility after curing). Straight section curing 1,5 hour at a temperature 165°C [Green,2012].

Test arrangement according to fig. 3 with the following parameters: L_i = 1020 mm, L_{pr} = 230 mm (tape EGSB 2969 0, 15 x 20), L_{sh} = 160 mm (tape 215.55 0,1 x 20). Tapes for protection against corona in the coil straight section pressed along with the insulation; their mutual overlap – 30 mm.

Values found for the breakdown voltage U break. (kV), calculated mean value of the breakdown voltage U center (kV), and the unit dielectric strength E (kV/mm) Tab. 5

	U break. (kV) – straight coil part molded insulation Calmica 70 0867			U center (kV)	E (kV/mm)
U_n = 11 kV t =2,3 mm	84,5	79,6	73,5	79,2	34,4

Table 5. Measured values, mean breakdown voltage and unit strength

Test arrangement according to fig. 3 with the following parameters: L_{pr} = 120 mm (tape EGSB 2969 0,15 x 20), L_{sh} = 100 mm (tape 215.55 0,1 x 20). Mutual overlap of tapes for protection against corona 20 mm.

Values found for the breakdown voltage U break. (kV), calculated mean value of the breakdown voltage U center (kV), and the unit dielectric strength E (kV/mm) Tab. 6

	U break. (kV) – face uncured insulation Calmica 70 0867			U center (kV)	E (kV/mm)
U_n = 11 kV t = 1,9 mm	37,9	35,0	34,5	35,8	18,6

Table 6. Measured values, mean breakdown voltage and unit strength

After the straight section pressing, the front sections of the coil were wrapped with the shrink lace and the coil was put into the oven for 10 hours at the temperature of 130°C. See test arrangement uncured forehead.

Values found for the breakdown voltage $U_{break.}$ (kV), calculated mean value of the breakdown voltage U_{center} (kV), and the unit dielectric strength E (kV/mm) Tab. 7

	$U_{break.}$ (kV) – face cured insulation Calmica 70 0867			U_{center} (kV)	E (kV/mm)
U_n = 11 kV t = 1,9 mm	45,1	41,8	49,9	45,6	23,8

Table 7. Measured values, mean breakdown voltage and unit strength

The measurement was carried out in the arrangement according to the applicable standard; the length of the measurement electrode was 820 mm, shading strips 50 mm, the gap 3 mm.

Loss factor values measured at 20°C; graphics course Fig. 5 [Green,2012].

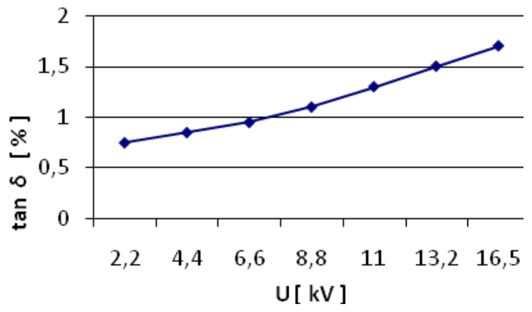

Figure 5. Process tan δ loss factor – insulation Calmica 70 0867; t = 2,3 mm

7 CONCLUSION

The measurement results of coils, i.e. voltage tests of the cured pressed straight section, cured and uncured front sections, and the graphical representation of the tan δ complied with requirements of international standards.

The average unit dielectric strength of the cured pressed straight section of 38.8 kV/mm represents a relatively high value of the dielectric strength for the coils of these voltage levels (for the discontinuous system, the insulation on the basis of the Relanex glass is used, which has the dielectric strength). The average unit dielectric strength of the uncured insulation of the front sections of 19.8 kV/mm represents the standard value of the dielectric strength for this application, and is comparable to the value of the dielectric strength of uncured front sections in the discontinuous system when the LSU tape is used.

Once the coil front sections are cured in the oven, their dielectric strength will increase by 3 kV/mm in average. For the possibility of statistical evaluation of the Calmica uncured insulation, measurements on mandrels were carried out.

The results correspond to the values measured on coils when the values of deviations of the mean of breakdown voltages differ less than 0.5 of the standard deviation of the standardized normal distribution of the mandrel breakdown voltages. Two coils also insulated by the automatic wrapping machine with the Calmica tape had the tape properly laid and tightened, and the median of the breakdown voltage of the uncured insulation was 17.7 kV/mm (which is less than with coils insulated manually due to a high number of wraps; it applies generally that the higher the insulation thickness is, the less is its unit dielectric strength in kV/mm). The technical parameters of the automatic wrapping machine with the wrapping head meet the insulation of open coils, i.e. the coils with a high step (two-pole machines) and, of course, the insulation of bars (half-coils) where the head use is allowed along the entire length of the bar. For the coils with a small opening, insulating by the wrapping machine as opposed to the discontinuous system loses importance.

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