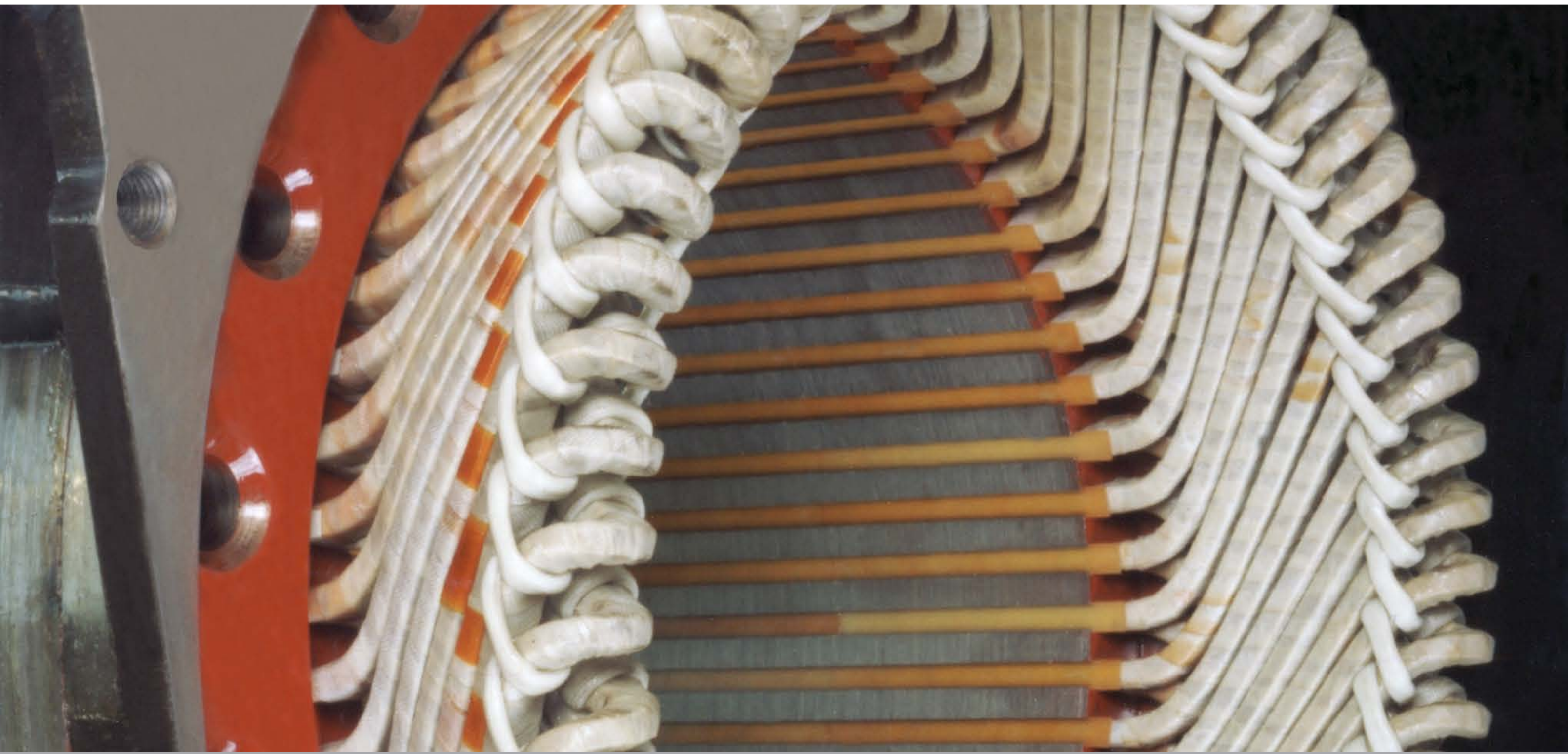
Insulation system VEMoDUR-VPI-200

for inverter-fed traction motors
with high rated voltages



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Outline

Traction motors in the voltage range up to 3,000 V and with powers up to 1 MW and above have been manufactured at VEM Elektroantriebe Dresden GmbH (Sachsenwerk/Dresden) since the 1950s. The stator windings of the three-phase traction machines supplied today are designed as form-wound coil windings with the proven insulation system VEMoDUR -VPI-200. The insulation system was subjected to extensive performance tests, with the aim of achieving even higher rated voltages and at the same time proving the resistance to the pulse-shaped voltage stresses which occur in use with modern inverters. Particular attention was paid in this respect to electrical life tests with different qualities of winding wire, in order to reach conclusions on their fields of application. It could be shown on real stator windings with the VEMoDUR-VPI-200 insulating system, that the winding insulation is unquestionably able to satisfy today's service life requirements, even when subjected to high voltage stresses.

Introduction

The 1960s already saw intensive efforts in electrical engineering do develop insulation systems which would allow a greater utilisation of the electrical machines and permit higher thermal loads. These systems were at the same time to be insensitive to moisture and dirt influences.

Traction motor manufacture provided particular impetus for such developments, though the results were then also to be applied for stationary drives subjected to high thermal stresses.

Sachsenwerk Dresden at that time introduced an insulation of the thermal class H, which was made up essentially of mica, glass and silicone rubber. The necessary moisture protection was achieved by means of a repeated impregnation with silicone varnish (on the basis of polycondensation resin). Several hundred traction motors for diesel-electric locomotives are still today, after a service life of almost 30 years, operating under tropical conditions with this Sachsenwerk insulation system, and that to the full satisfaction of the users. The development of additively cross-linked silicone resins in the 1970s was a pre-requisite for the introduction of class H and 200 insulation systems using the clearly technically and economically favourable vacuum-pressure impregnation process.

The materials available were again glass and mica, together with polyimide film and insulating wrappings comprising aromatic polyamide fibres. Sachsenwerk Dresden carried out the corresponding development and prototype studies at an

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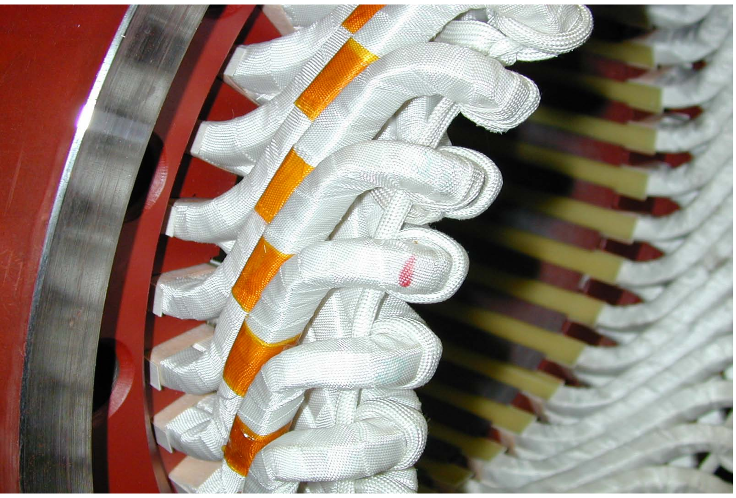
early stage and in close cooperation with the suppliers. The result of this development work was the introduction of the insulation system VEMoDUR-VPI-200, which has so far been applied extremely successfully, even under difficult environmental conditions, for 600 locomotive motors (main-line and heavy industrial locomotives with powers from 350 ...1,050 kW and rated voltages up to 1,800 V) and more than 10000 local public transport motors (three-phase asynchronous and DC motors for train sets, city railways and trams and trolley buses with powers from 50...500 kW and rated voltages up to 3000 V). In addition, the insulation system VEMoDUR-VPI-200 is also successfully applied for more than 1000 traction generators (diesel-electric locomotives, train sets and mining trucks as well as for auxiliary units with powers from 50...5000 kVA and rated voltages up to 2800 V).



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Description of the insulation system

The insulation system VEMoDUR-VPI-200 has been designed particularly for the use in class 200 traction motors according to IEC 349. Taking into consideration the special duty of traction motors and generators, which involves highly cyclic stresses and thus thermal cycles in the winding, the permissible temperature limit has been specified as 240°C, or 250°C for completely closed machines, in the relevant IEC provisions for traction machines.

Traction motors are to an increasing extent being fed with modern voltage-link inverters using IGBT semiconductors. The extremely short switching times of the components lead to pulse-shaped voltage peaks which, dependent on the system parameters (link voltage, pulse frequency,

cable type and length), exert stress above all on the winding insulation of the machines. The following is a report on the resistance of the insulation system to these pulse-shaped voltage stresses.

These extreme thermal requirements are already taken into account in the selection of the individual insulating materials.

The following materials are used for the main components:

Component	Insulating material
Winding wire insulation (turn insulation)	polyimide film; polyimide film/ glass silk braiding
Taping/packings (main and end winding insulation) made from arom. polyamide	mica-glass silk tapes with aramide-fibre-reinforced mica paper/ aromatic polyamide paper/ aromatic polyamide
Impregnating material	silicone impregnating resin (modified phenyl-methyl resin with platinum catalyser)

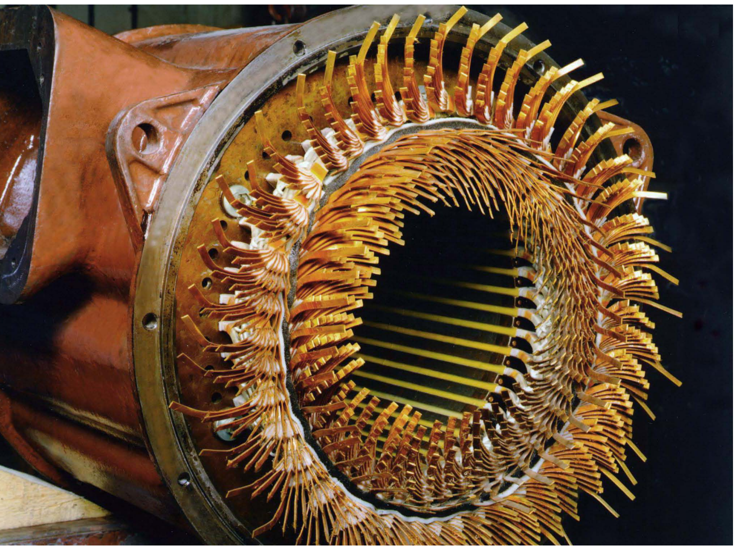
Table 1

Insulation systems using the components above have proved successful for many years. The excellent thermal properties, especially the high thermal overload capability, are described in various references [1 - 6]. The extensive experience gathered with the insulation system VEMoDUR-VPI-200 in the operation of a large number of different traction motors can be seen as proof of its thermal endurance, eliminating the need for a separate functional evaluation as is common according to IEC 60034-18 [7 and 8].

To determine the electrical life of the winding insulation, as detailed below, an experimental stator with form-wound coils, having coil turns which were cut on the front face, was manufactured under series production conditions (Fig. 1). The coil turns were cut on the front face before impregnation and the resultant gaps between the turns were filled with a special impregnating resin.

The turn insulation (winding insulation) in one and the same stator was made both of polyimide film (Kapton/FN) and polyimide film in combination with glass silk braiding, making it possible to comparethe two materials directly.

The main insulation on the coil sides and end windings consisted of mica/glass silk tapes with aramide-fibre-reinforced mica paper and was vacuum-pressure impregnated with silicone resin. The thickness of the insulation was dimensioned by selecting the number of layers as a function of the rated voltage of the traction motor. The rated voltage of the experimental motor was 1,200 V. All insulating materials applied satisfied the technical characteristics specified in the VEM Technical Terms of Delivery.



(Figure 1) experimental stator

Simulation of inverter stress

The impact of the impulse voltage stress on the turn insulation of low voltage machines provided solely with enamelled wire windings has already been investigated in detail [9 to 11]. It was found that the typical inverter-related voltage pulse rise times of some hundred ns, which result in a non-linear voltage distribution in the winding, may lead to electrical overloading of the turn insulation.
Depending on the amplitude and frequency of the voltage pulses, this electrical overloading can reduce the winding life to an impermissible extent. Especially critical is the occurrence of partial discharges as a result of the electrical overloading. Based on these findings, the limit curve for the permissible impulse voltage at the motor terminals has been revised as published in supplement 2 to DIN VDE 0530 [12].
No generally applicable investigation results are known for machines with form-wound windings and higher rated voltages. Only the limit curves of the permissible impulse voltage for such insulation systems have been published, taking the form of a statistical survey rather than standardised data [13].
The maximum permissible impulse voltage reported in this publication, without consideration of the impulse rise time and without any description of the winding insulation, is 1.85 kV. At this point it should be noted that traction machines, and therefore also their insulation systems, are excluded from the scope of the IEC 60034-1 and the subordinate standards concerning the functional evaluation of the insulation systems IEC 60034-18. In spite of this, one of the most important principles of the functional evaluation in case of an inverter drive, the life test with parameters which are typical for inverter drives, has been applied for the insulation system VEMoDUR-VPI-200. Meanwhile, this principle has found its way into the standard IEC 60034-18-42 [14] and ensures the long-term resistance to the heightened electrical stresses for the so called insulation systems of the type II, where partial discharges can occur during the operation of the machine which are due to the loading of the inverter.
The question to be resolved was, therefore, the one concerning the permissible electrical stress from the inverters, especially in view of the fact that the Corona discharge resistance of polyimide film is the subject of in-depth discussions on an

international scale. The dependence of the electrical life of the turn insulation on the voltage shape is shown in [9]. Below the partial-discharge inception voltage, however, the differences between unipolar impulse voltage, 50 Hz a.c. voltage, and real inverter stress are small. The life tests presented here were thus carried out with 50 Hz a.c. voltage. The time to failure measured was converted into an expected life time under inverter stress by counting the number of half-waves occurring before breakdown.

Results/preliminary tests

The experimental stator winding was manufactured under series production conditions and passed all standard high-potential tests, plus an additional water-submersion type test (Fig. 2). The distribution function of the breakdown voltage between two adjacent turns was then measured in a voltage rise test.

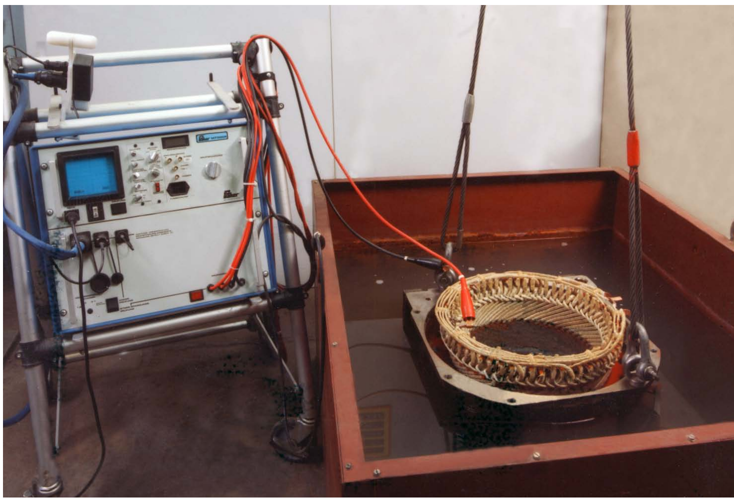
A mutual influence between successive breakdown tests was excluded by leaving one turn between the two windings unstressed.

The distribution functions of the breakdown voltage (Fig. 3) can be approximated for both winding wire types by means of a Gaussian distribution.

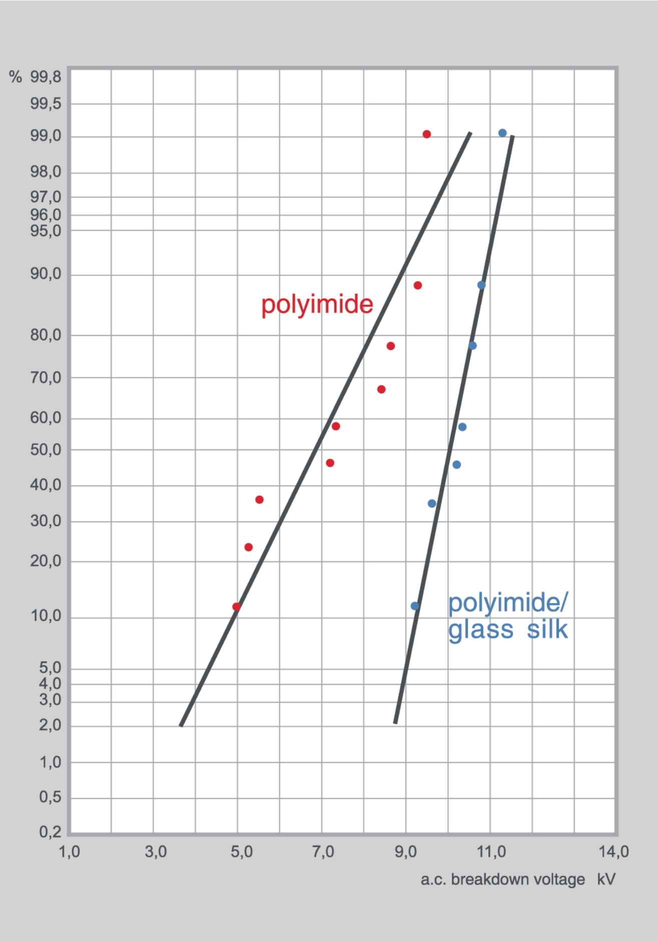
The mean breakdown voltage for the wires insulated solely with polyimide film is 6.8 kV, while for those with additional glass silk braiding this voltage is 10 kV. These values lie far beyond the operating stresses, thus verifying a faultless initial condition. Based on these results, three different a.c. test voltages were derived for the life tests on each wire type and applied as constant voltages until the breakdown of the individual windings. The life tests were performed at room temperature, since the outstanding thermal properties of the VEMoDUR-VPI-200 insulation system have already been established by our operating experience (see section „Description of the insulation system“).

Electrical life

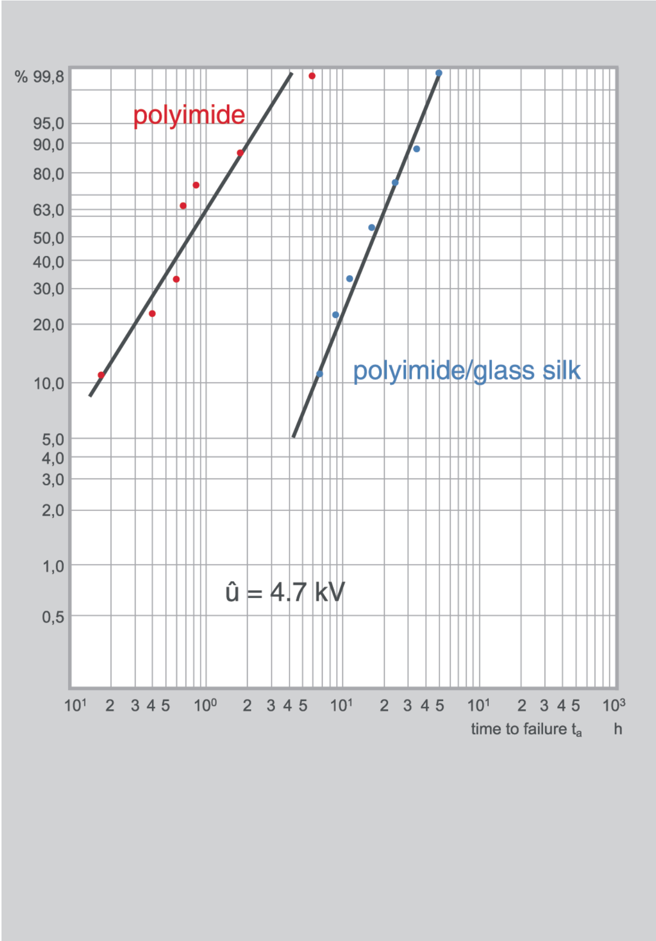
The standard Weibull distribution was used for the statistical evaluation of the times to failure of the winding insulation. One of the selected test voltages was applied for both wire types (û = 4.7 kV). Figure 4 shows that the mean time to failure of the winding wires with exclusively polyimide film insulation is, as expected, comparatively low at this stress.



(Figure 2) water-submersion type test

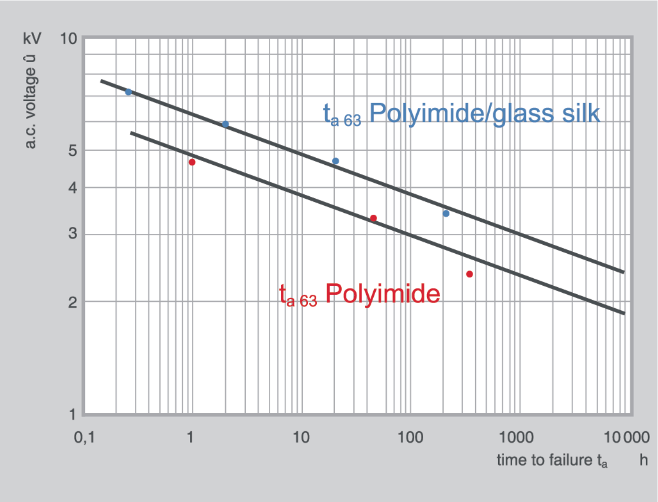


(Figure 3) cumulative frequency of the breakdown voltage of the windings

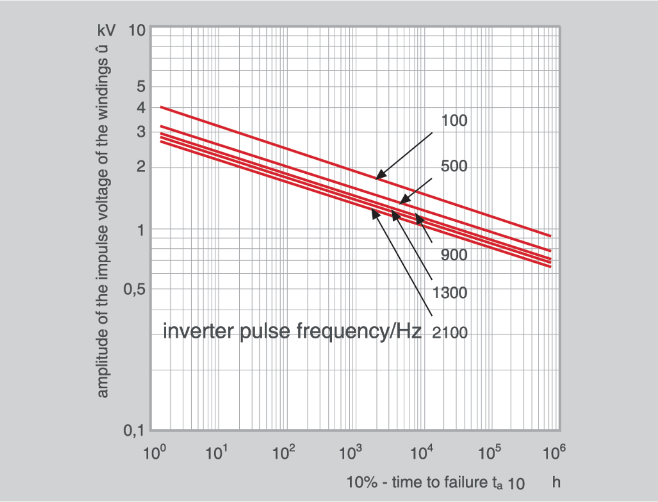


(Figure 4) cumulative frequency of the time to failure

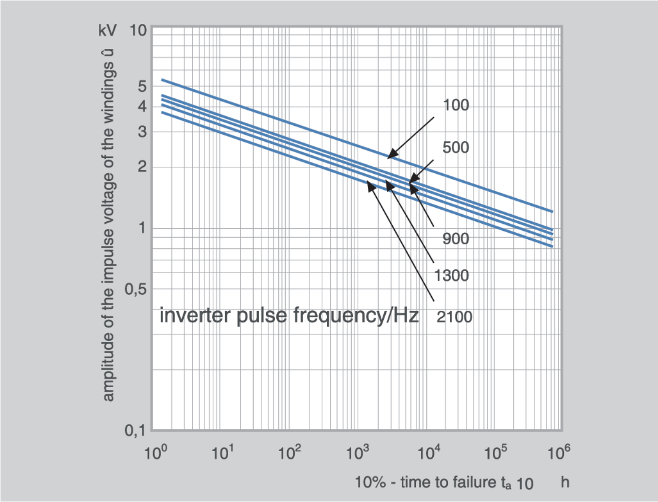
Winding wires with an additional glass silk braiding show a markedly higher mean time to failure ($t_{a\,63}$ = 20 h).
The mean times to failure derived from such distribution functions at test voltages in the range û = 2.3 ... 7.2 kV were plotted into the life time diagram (Fig. 5). In the log-log diagram, the life time characteristics are parallel lines with a rate of rise (life time exponents) of n = 9, i.e. approximately the same ageing mechanism is applicable to the two winding wire types.
It is obviously the polyimide film which determines the ageing process rather than the glass silk braiding, which only shifts the position parameter of the life characteristic. As a comparison, a life exponent of n = 9.5 is reported for the epoxy resin insulations of high-voltage machines [15]. From this it follows that the electrical ageing process of the winding insulation in the VEMoDUR-VPI-200 insulation system is similar to that in other insulation systems of rotating electrical machines. Since the ageing mechanism does not change up to the highest a.c. test voltage applied, it can be concluded that, at these high stresses, the polyimide film is not, as might have been expected, progressively degraded by the presence of partial discharges.
The electrical ageing can be calculated by means of the relationship $U_d = k_d \bullet ta^{-1/n}$ (k_d = position parameter).
To predict the permissible stress imposed by the inverter on the turn insulation, the life characteristic for the 10% quantile of the distribution function was determined as for Figure 3, and this was used to calculate the number of half waves occurring until break-down. By dividing this number by the inverter pulse frequency as a measure of the frequency of pulse voltage stress, a new life characteristic with the inverter pulse frequency as parameters is obtained (Figures 6 and 7). As inverter pulse frequencies, only the values in the range of 100 Hz to approx. 2 kHz which are relevant for traction machines were taken into account.
From the life characteristics under inverter stress, extrapolated for 30 years of uninterrupted operation, it can be recognised that the permissible turn voltages for the winding wires insulated solely with polyimide film (Fig. 6) lie somewhat below 1 kV, whereas those for the winding wires with additional glass-silk braiding (Fig. 7) are 1 kV.



(Figure 5) mean time to failure at 50 Hz



(Figure 6) service life of the polyimide winding insulation



(Figure 7) service life of the polyimide-glass silk winding insulation

Conclusions

The test results obtained for a stator winding using the insulation system VEMoDUR-VPI-200 show that a high resistance to the electrical inverter stress is achieved even when using standard winding wires based on polyimide film of type FN (FEP), provided a precise technology is maintained in the winding manufacture. For higher rated voltages the winding wire with additional glass silk braiding is available.

By taking the impulse voltage to be expected at the traction motor terminals and the voltage distribution in the winding into account, it is possible to calculate the electrical life of the insulation system.

Compared to fed-in windings with round wires (wire-wound windings), form-wound windings with flat wires offer the advantage that the actual turn-to-turn impulse voltage within a coil is also known and can be used to calculate the electrical life.

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References

[1] von Roll Isola
„Kaptonisolierte Drähte - ein sicheres System“, Firmenschrift Schweizerische Isola-Werke, 1989, pp.1-8.

[2] H.P. Mayer, W. Sorg
„Kapton Polyimid: Folie mit außergewöhnlichen Eigenschaften“, Industrie Service Ausgabe 12/90, pp. 32-34, 37.

[3] B. Haberthür
„VPI for Class H Tractions-Motors“, IEEE, 1983, pp. 406-413.

[4] F. Galliker
„Bauformen der BBC-Fahrmotoren für alle kommenden Zugförderungsaufgaben“, Brown Boweri Mitt. 12/84, pp. 545-557.

[5] H.P. Mayr, D. Stone
„Fortschrittliche Isoliersysteme für die Fahrmotoren moderner Hochgeschwindigkeitszüge“, eb – Elektrische Bahnen 92, 1994, pp. 48-50.

[6] H. Brandes
„Tränkmittel in der Elektroindustrie“, Firmenschrift von Roll Isola, 1995, pp. 1-10.

[7] IEC 34-18-1: „Functional evaluation of insulation systems for rotating electrical machines
Part 1: General guidelines“, 1992-02, pp.1-45.

[8] IEC 34-18-31: „Functional evaluation of insulation systems for rotating electrical machines
Section 31: Test procedures for form-wound windings – Thermal evaluation and classification for insulation systems used in machines up to and including 50 MVA and 15 kV“, 1992-07, pp. 1-27.

[9] M. Kaufhold
„Elektrisches Verhalten der Windungsisolierung von Niederspannungsmaschinen bei Speisung durch Pulsumrichter“, Diss., TU Dresden, 1994, Fortschr. Ber. VDI-Reihe 21 Nr. 172. Düsseldorf: VDI-Verlag 1995.

[10] M. Berth, M. Eberhardt, J. Speck
„Potential Grading and Wave Parameters of Winding Phases of Induction Motors“, 9th International Symposium on High Voltage Engineering (ISH), Graz, 20.08. - 01.09.95.

[11] M. Berth, M. Eberhardt, M. Kaufhold, J. Speck, H. Auinger
„Elektrische Belastung und Ausfallverhalten der Wicklungsisolierung von Asynchronmaschinen bei Umrichterspeisung“, ELEKTRIE Berlin 49, 1995, 8/9.

[12] DIN VDE 0530 Beiblatt 2 (VDE 0530 Beiblatt 2) 04.94 (IEC 34-17-1992)
„Drehende elektrische Maschinen; Leitfaden für den Einsatz von umrichtergespeisten Induktionsmotoren mit Käfigläufer; Identisch mit IEC 34-17; 1992 (Report), (Abschnitt 9: Lebensdauer des Isoliersystems).

[13] E. Persson
„Transient Effects in Application of PWM Inverters to Induction Motors“, IEEE Transactions on Industrial Applications, Vol. 28, No. 5, Sept./Okt. 1992.

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[14] IEC/TS 60034-18-42 Ed.1
Rotating electrical machines – Part 18-42: Qualification and acceptance tests for partial discharge resistant machines fed from voltage converters

[15] Quint, R. Schuler, N. Didzun, F. Stobbe
„Entwicklungsstand der Isolationstechnologie bei rotierenden elektrischen Hochspannungs-Maschinen“, ETG - Fachtagung, Würzburg 09/94, pp. 101-114.

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