Electrical Stress and Failure Mechanism of the Winding Insulation in PWM-Inverter-Fed Low-Voltage Induction Motors

Martin Kaufhold, *Member, IEEE*, Herbert Auinger, Matthias Berth, Joachim Speck, and Martin Eberhardt

***Abstract*—The winding insulation of low-voltage induction motors in adjustable-speed drive systems with voltage-fed inverters is substantially more stressed than in line-powered motors. Consequently, this operation is subject to limitations depending on the electrical stress and on the failure behavior of the winding insulation. Actual recommendations do not consider sufficiently the physics behind these phenomena and contain large utilizable reserves.**

***Index Terms*—Cable length, converter, electrical breakdown, electrical stress, impulse voltage, insulated gate bipolar transistor, life time, low-voltage machines, main insulation, partial discharge, phase insulation, rise time, stress limit, switching frequency, turn insulation, voltage distribution.**

I. Introduction

In THE lower and medium-power ranges, adjustable-speed drive systems are produced today predominantly with voltage-fed inverters (VFI's). The dc-link voltage of the intermediate circuit of a VFI is mostly supplied by a power line rectifier. Power electronic switches are used to provide square-wave pulsewidth modulated voltage impulses at the output terminals of the inverter, so that a nearly sinusoidal current appears in the phases of the motor winding. This principle is called pulsewidth modulation (PWM).

PWM inverters work with switching frequencies of up to 20 kHz. Using insulated gate bipolar transistors (IGBT's) the switching times are on the order of 100 ns. This paper shows the physical dependencies which lead at such voltage impulses to an increased electrical stress on the winding insulation, particularly, the turn insulation. In addition, the aging mechanism and the lifetime of the winding insulation as a weak point in the insulating system is discussed [1]–[3]. On this basis, the technical limitations imposed by the winding insulation on the operation of induction motors subjected to PWM inverter voltages are shown.

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M. Kaufhold and H. Auinger are with Siemens AG, 13624 Berlin, Germany (e-mail: martin.kaufhold@blns.siemens.de).

M. Berth is with the High Voltage Group, ABB Corporate Research Ltd., Baden, Switzerland.

J. Speck and M. Eberhardt are with Dresden University of Technology, Dresden, Germany (e-mail: speck@ehhn1.et.tu-dresden.de).

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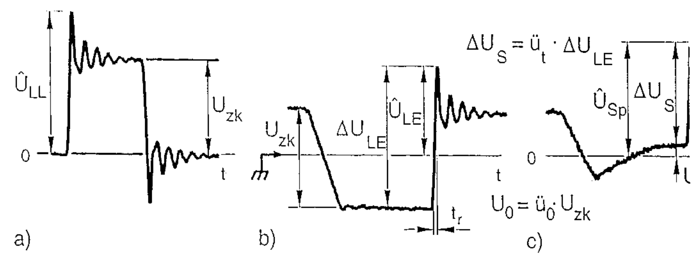

Fig. 1. Typical motor voltage characteristics during PWM inverter operation. (a) Line-to-line terminal voltage. (b) Line-to-earth terminal voltage. (c) Voltage crossing the first coil.

II. Electrical Stress of the Winding Insulation

A. Insulating System of the Stator Winding

The insulating system of stator windings consists of the main and phase insulation and turn insulation, as well. The main or slot insulation separates the winding from the stator core. The different potentials of the individual phases are separated from each other by the phase insulation (phase separation). The turn insulation between adjacent turns inside the coils consists of the wire enamel and an impregnating resin or varnish. Due to the random-wound windings of low-voltage induction motors and the fact that coils of larger machines are usually wound from several parallel wires, there is a good likelihood that the starting and end turn of one coil will be adjacent. Thus, the entire coil voltage will appear between two adjacent wires. Under unfavorable conditions, the turn insulation can even be subjected to the voltage drop over multiple coils or coil groups.

B. Voltages at the Motor Terminals in Converter Operation

At the inverter output terminals, voltage impulses are created with amplitudes corresponding to the voltage of the dc-link circuit. Caused by voltage drops, the dc-link voltage depends upon the load conditions and can exceed or fall below its nominal value, according to the direction of the power flow. The short rise times of the voltage impulses at the inverter output result in traveling waves on the motor cable. Multiple reflections at both ends of the motor cable lead to oscillating impulse voltages at the motor terminals. If the rise time of the voltage impulses from the converter is less than twice the propagation time of the connecting cable, the voltage doubling effect of line reflections lead to voltage amplitudes up to two times the dc-link voltage [3].

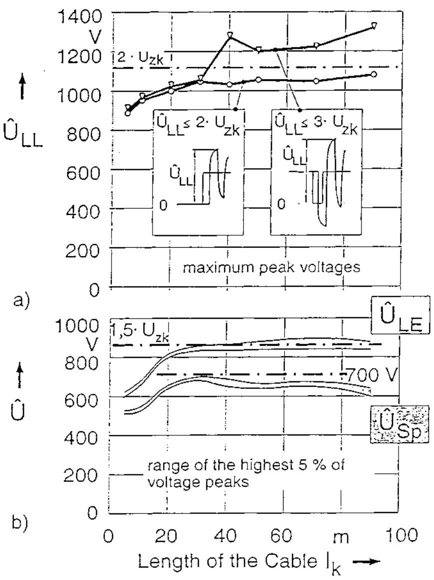

Fig. 2. Maximum motor terminal voltages during PWM inverter operation depending on the cable length. Pulse frequency 9 kHz, 4-kW induction motor. (a) DC-link voltage $U_{zk} = 560$ V. (b) Rise time $t_r = 100$ ns.

Fig. 1(a) shows a typical curve for the line-to-line voltage at the motor terminals. Its peak value $\hat{U}_{\rm LL}$ represents the maximum electrical stress on the phase insulation.

Measurements on inverter-fed motors [Fig. 2(a)] have shown that, with a long motor cable, the theoretical maximum voltage of twice the dc-link voltage in the case of a single switch ($\hat{U}_{\rm LL\ max} = 2 \bullet U_{zk}$) is nearly reached. Multiple switches, theoretically, can lead to maximal peak voltages up to three times the dc-link voltage ($\hat{U}_{{\rm LL}\,max} = 3 \bullet U_{zk}$). However, as shown in Fig. 2(a), this value will not be reached at all due to the cable damping.

The maximum electrical stress on the main insulation (slot insulation) is determined by the peak value of the line-to-ground voltage $\hat{U}_{\rm LE}$ [Fig. 1(b)]. The peak values of the line-to-ground voltage are lower than those of the line-to-line voltage. In the case of a well-grounded dc-link circuit, they reach values up to $1.5 \bullet U_{zk}$. The performed measurements yield somewhat higher values [Fig. 2(b)], which is due to slight shifts of the dc-link voltage as a consequence of the six-pulse rectification (common-mode effect). To avoid short circuiting of the dc-link circuit, the recovery times of IGBT's require dead times between switchings of the semiconductors in one leg of the output bridge. This makes the pulsewidths of the line-to-ground voltage so long that switching does not occur in the nonbuilt-up state until the cable length exceed 100 m, i.e., multiple switches do not affect the line-to-ground voltages.

The transient voltage steps $\Delta U_{\rm LE}$ of the voltage between the motor terminals and the stator core distribute unevenly over the coils of the winding. Depending upon the rise time, this voltage distribution will be determined by inductive and/or capacitive coupling. It has turned out to make sense to define an amplitude ratio $\ddot{u}_t$ of the voltage step on the line-end coil ΔU_S [Fig. 1(c)] to the voltage step of the line-to-ground voltage $\Delta U_{\rm LE}$, as a function of the rise time t_r [3]

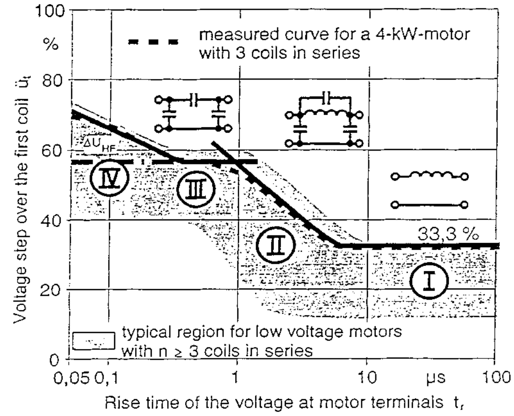

Fig. 3. Distribution mechanism of the transient voltage step over the first coil.

$$\ddot{u}_t(t_r) = \frac{\Delta U_S}{\Delta U_{\rm LE}}. \tag{2.1}$$

According to Fig. 3, four characteristic ranges can be distinguished: For very long rise times, only inductive couplings are effective and the terminal voltage is distributed evenly over the coils of the winding (*range I*). In *range II*, inductive and capacitive elements produce a behavior similar to that of transmission lines, while the propagation times of typical windings are in the range of several microseconds [4]. With rise times of approximately 200 ns–1μs typical for PWM inverters, the transient distribution of fast voltages in motor windings is determined primarily by capacitive couplings (*range III*). A procedure based on the four-pole theory [4], [7] made it possible to determine the voltage distribution along the winding in numerous motors of various frame sizes without tapped windings, by means of measurements at the motor terminals.

Utilizing this procedure, it could be shown that between 40%–60% of the voltage step at the motor terminal will drop over the entrance coil [Fig. 3]. This result could be confirmed by measurements on taped motor windings [3].

At shorter rise times (50–200 ns), portions of the windings can be excited to HF oscillations. In *range IV*, this can lead in unfavorable cases to coil voltages up to $\ddot{u}_t$ =70% of the terminal voltage. Due to the distortion of the voltage impulses as they pass through long transmission lines, such short rise times occur at the motor terminals only when the motor cable is very short [3]. A combination of extremely short rise times with voltage amplitudes of $\Delta U_{\rm LE} = 2 \bullet U_{zk}$, therefore, can only be expected in rare cases.

The inductances and capacitances of stator windings form a resonance circuit, with resonance frequencies of several tens to hundreds of kilohertz. For that reason, each switching impulse shows voltage oscillations in the winding which last several microseconds. If an additional switching impulse occurs during the time, the voltage U_0 which is on the first coil at the moment is overlaid by the transient voltage ΔU_S [Fig. 1(c)]. The voltage

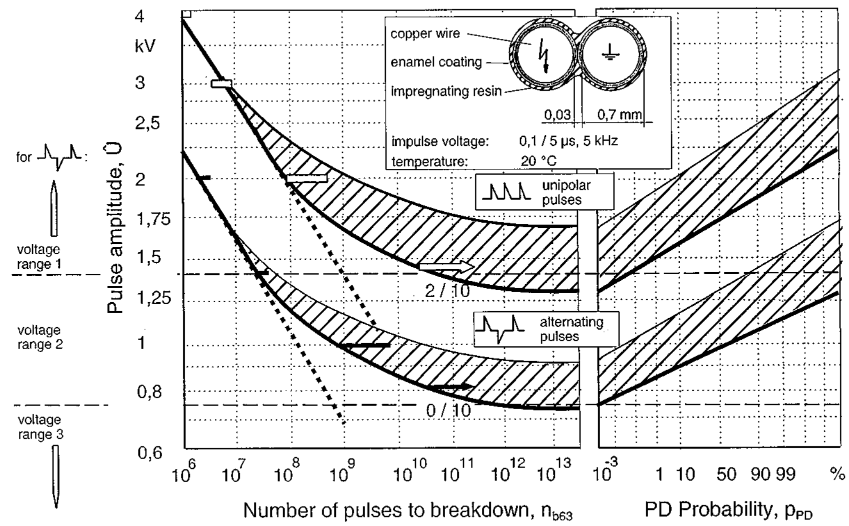

Fig. 4. Relationship between partial discharge and breakdown behavior of typical turn insulations.

U_0 can be given as the amplitude ratio $\ddot{u}_0$, related to the dc-link voltage

$$\ddot{u}_0(pw) = \frac{U_0}{U_{zk}}. \tag{2.2}$$

When pulsewidth is critical $pw = pw_{\text{crit}}$ at least individual impulses may lead to increased voltages over the first coil. Measurements have shown that the voltage U_0 can amount to approximately 15% of the dc-link voltage.

The height of the amplitude ratios $\ddot{u}_t$ and $\ddot{u}_0$ depends on the winding design.

The peak value of the voltage over the first coil $\hat{U}_{Sp}$ can be found from the sum of the transient voltage amplitude ΔU_S and the voltage U_0 [Fig. 1(c)]

$$U_{Sp} = \Delta U_S + U_0 = \Delta U_{\text{LE}} \bullet \ddot{u}_t(t_r) + U_{zk} \bullet \ddot{u}_0(pw_{\text{crit}}). \tag{2.3}$$

In Fig. 2(b), measured maximum peak values of the voltage over the first coil are plotted against the length of the motor cable. The highest voltage amplitudes of four test motors occurred on a 4-kW motor with $n = 3$ coils in series. Through model measurements, it was possible to find the values $\ddot{u}_{t\,\text{cap}}$ =56% and $\ddot{u}_0$ =13% for this motor (where $pw_{\text{crit}} = 5\,\mu$s). Using (2.3), and with an intermediate circuit voltage of $U_{zk} = 560$ V, this results in a maximum voltage over the first coil of $\hat{U}_{Sp} = 2 \bullet 560$ V $\bullet\, 0.56 + 560$ V $\bullet\, 0.13 = 700$ V [see Fig. 2(b)].

In numerous measurements, it was found that the voltages over the first coil are the maximum values when the length of the cable between converter and motor is some tens of meters and both the converter and the motor are grounded hard, even for high frequencies.

As a consequence of the alternating polarity of the voltage slopes, both the main and turn insulation are electrically stressed with voltage impulses of alternating polarity.

III. Failure Mechanism of the Turn Insulation

The partial discharge (PD) and breakdown behavior of different turn insulations were investigated with typical voltages as they occur in PWM inverter drive systems [3].

A. Model Test Specimens and Experimental Setup

As a model of the turn insulation, coils of two parallel-wound and immersion-impregnated enameled wires were used (polyesterimide enamel, length approximatel 2 m, inside radius of the ring coils approximately 2 cm, ten bandaged turns). Various conductor diameters enamel and impregnation thicknesses were investigated at temperatures between 20 °Cand the maximum operating temperature of 155 °C. The model insulations used meet the minimum requirements of the insulation system employed for standard motors with rated power up to 200 kW and rated for line voltages of up to 690 V. Often, wires with an insulation performing higher electrical strength are used [1], [9].

For detecting partial discharges at fast transient impulse voltages, a photomultiplier was used, which converts the radiation emitted in the discharge process into a photoelectron current. In this way, single partial discharge pulses during the voltage impulse application were recorded. The effectiveness of this procedure was approved by means of a simultaneous optical and electrical measuring of partial discharge under ac voltage conditions.

B. Relation Between PD's and Lifetime

The PD behavior of the turn insulation was described in terms of the relative frequencies or probabilities, respectively, of PD's depending on the voltage amplitudes, which were measured on a pulse-by-pulse basis. During these measurements, PD's were optically detected for each and every voltage pulse over a sufficiently long period of time. 99% PD probability, for example, means that, out of 1 000 000 voltage pulses, 990 000 of them created at least one partial discharge in the specimen. Since both the discharge process and the properties of the test specimens show stochastic scattering, the measured distribution functions $p_{\text{PD}}(\hat{U})$ were plotted as areas (Fig. 4). The characteristic curves of both lifetime as well as partial discharge probability show three typical voltage ranges.

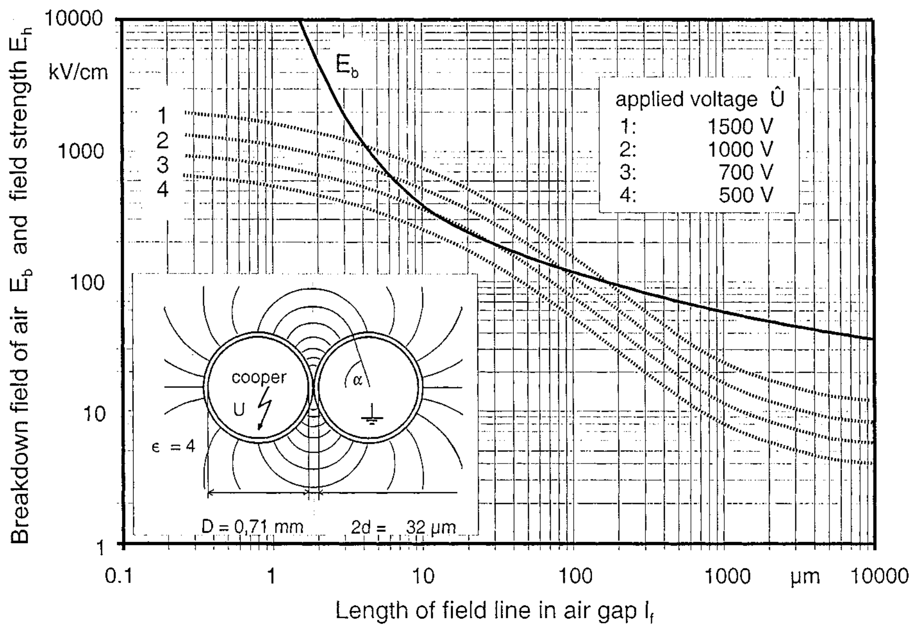

Fig. 5. Calculation of the PD inception voltage. Comparison of electrical stress and strength of the air along the fieldlines in a gap of a model turn insulation.

In *range 1*, at high voltages, virtually each voltage impulse leads to at least one partial discharge, and the lifetime curves follow the well-known lifetime equation

$$\hat{U}_{b1} = k_b \bullet n_{b1}^{-1/m} \tag{3.1}$$

with the parameters $m \approx 6.5$ and $k_d \approx 18$ kV for the model turn insulation measured with alternating impulse polarity.

In *range 2*, the lifetime curves "move" to higher breakdown impulse numbers n_{b2}. These can be calculated from the breakdown impulse number in range 1 and the probability of partial discharge occurrence $0 < p_{\rm PD} < 100\%$ [3].

$$n_{b2} = \frac{n_{b1}(\hat{U})}{p_{\rm PD}(\hat{U})}. \tag{3.2}$$

In *range 3*, no partial discharges occur. For that reason, no breakdown was observed at these voltages either. These observations lead to the following conclusions.

Failures of the turn insulation due to the converter feeding start from partial discharges in the air gap between two adjacent wires [8]. The breakdown of the air gap with the eruptive flow of charge carriers causes the accumulation of charge densities on the surfaces of the insulation and results in an electrical aging of the insulation through erosion [6]. If the insulation is completely eroded at the weakest spot, the discharge leads directly to a breakdown of the turn insulation (erosion breakdown). Charge densities in the solids close to the insulating surface and dielectric high-frequency heating suppor, but do not cause, the breakdown, which does not occur without PD [3].

C. Calculation of the PD Inception Voltage

Generally, the complete or partial breakdown of an air gap can be expected where the highest electrical field strength $\hat{E}_h$ (electrical stress) reaches or exceeds the breakdown field strength $\hat{E}_b$ (electrical strength) of the air. For the model turn insulation shown in Fig. 5, this condition is fulfilled with an applied voltage of $\hat{U} = 700$ V on field lines with $\alpha = 13°$ and a length of 20 μm. Both on shorter field lines, which are closer to the contact point of the enameled wires, and on longer ones, at this voltage no discharges are to be expected. At higher voltages, the PD inception condition is fulfilled over a greater area of the surface, and so the probability of the occurrence of partial discharges is also greater. At lower voltages, the breakdown field strength of air is not exceeded at any location. Thus, the calculated voltage $\hat{U} = 700$ V can be interpreted as the PD inception voltage $\hat{U}_i$ of the calculation model.

The partial discharge inception voltages which have been calculated for various enamel coat thicknesses and conductor diameters and those measured under impulse voltage (Fig. 6) show a tendency which is the same in principle. With alternating polarity, however, the measured values are somewhat lower than expected, and with unipolar impulse voltages they are somewhat higher. The cause is a charge buildup on the enamel surface due to the partial discharge, which causes the electrical field strength in the air-filled gap to be elevated under alternating impulse stress and to be lowered under unipolar impulse stress [3], [8].

D. Influence of the Design and Temperature of the Insulation

The partial discharge inception voltage is higher, the thicker the enamel coat is. Doubling the thickness of the enamel coat, for example, from 20 to 40 μm raises the partial discharge inception voltage by about 30% (Fig. 6). The diameter of the conductors has no direct influence on the partial discharge inception voltage within the experimental data.

Calculations, partial discharge measurements, and long-term experiments [3], [6] have shown that the penetration of impregnant into the voids of the insulation can significantly increase the partial discharge voltage and, consequently, the breakdown time. This renders decisive importance to the impregnation of the windings of low-voltage motors, not only for heat transmis-

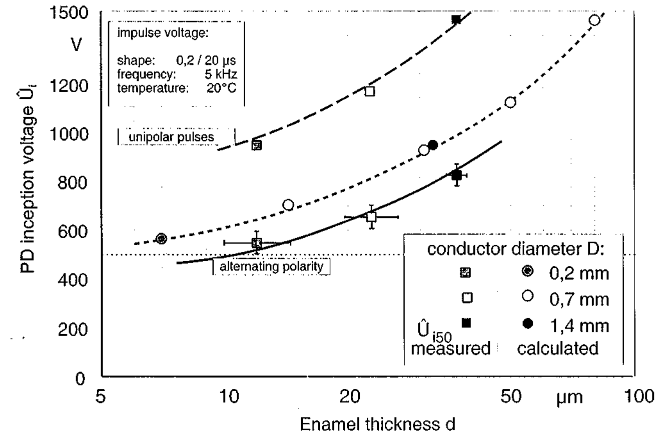

Fig. 6. Inception voltage depending on the thickness of the enamel layer in the turn insulation. Turn insulation (test sample) without impregnation.

sion and mechanical strength of the insulation, but also for the sake of their electrical strength. The quality level is governed by how the impregnating procedure which is used fills the voids between adjacent wires, and how they remain filled during the curing process.

Raising the temperature leads to a lowering of the partial discharge inception voltage, since the dielectric strength of the air decreases and the electrical field stress in the cavities rises due to the dielectric coefficient of solid insulating materials rising along with the temperature. Therefore, thermally induced accelerated electrical aging of the turn insulation is the consequence. Under typical converter stress, the partial discharge inception voltage is approximately 15% lower at 155 °C (the maximum permissible temperature in thermal class F) than at room temperature.

The lifetime tests which were performed on samples of impregnated model turn insulation with varying enamel coat thicknesses, and the dependency of the partial discharge inception voltage on the thickness of the enamel coat, as described, make it possible to state the maximum permissible voltages for electrical stress of the turn insulation of motors operating on converters. For example, for an enamel coat thickness of 12μm (corresponding to a wire diameter of 0.2 mm with diameter depending on enamel coat thickness of grade 1 [5], which represents the thinnest standardized enamel thickness), this results in a permissible voltage of 600 V, and for an enamel coat thickness of 30 ; μm (wire diameter approximately 1.4 mm), a permissible voltage of 900 V.

IV. Limitations for the Voltage at the Motor Terminals

Inverter-fed low-voltage motors can only be expected to have an adequate lifetime if no partial discharges occur, neither in the turn insulation nor in the phase or main insulation. For that reason, the voltages which occur, and the maximum permissible voltages for these insulations, must always be lower than their PD inception voltage.

To avoid an overstress of the turn insulation, the voltage over the first coil $\hat{U}_{Sp}$ must, therefore, not exceed the PD inception

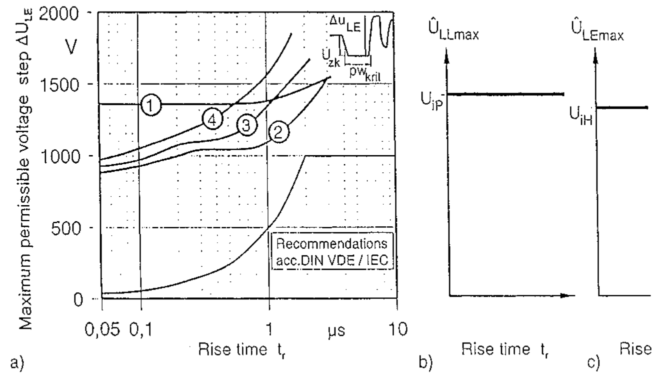

Fig. 7. (a) Maximum permissible voltages at the motor terminals at 155 °C dependent on the rise time imposed by turn insulation for test motors at 560-V dc-link voltage and $\{U_{iW}$; $\ddot{u}_0$; $n, \cdots$, number of series connected coils; $a, \cdots$, number of parallel branches$\}$: ① 0.37-kW motor $\{$640 V; 11%; $n = 4$; $a = 1\}$; ② 4-kW motor $\{$680 V; 13%; $n = 3$; $a = 2\}$; ③ 15-kW motor $\{$700 V; 15%; $n = 4$; $a = 2\}$; and ④ 55-kW motor $\{$710 V; 11%; $n = 4$; $a = 2\}$. (b) Phase insulation (schematic). (c) Main insulation (schematic).

voltage of the turn insulation U_{iw}, even under the most unfavorable circuit conditions, including multiple switchings with U_0 (2.2). Under this proviso, rearranging (2.3) makes it possible to calculate a limiting value for the amplitude of the transient voltage step $\Delta U_{\rm LE}$. This limiting value depends upon the type of winding, the PD inception voltage of the turn insulation U_{iw}, the rise time of the voltage impulses, and the dc-link voltage U_{zk}.

Fig. 7(a) shows corresponding limitation curves for the maximum permissible voltage $\Delta U_{\rm LE}$ for four test machines with single-layer winding. It was assumed, in general, that the turn insulation of wire enamel, grade 1, has been immersion impregnated one time and is subjected to the full coil voltage. The selected machines, with a relatively small number of coils wired in series, show a relatively high voltage over the first coil in the case of transmission-line behavior (see Fig. 3, *range II*). The capacitive voltage distribution of the 0.37- kW machine is favorable, and that of the 4-kW machine is particularly unfavorable.

For the comparison with earlier representations of limiting characteristic curves for the peak value of the line-to-line voltage $\hat{U}_{\rm LL}$ [1], [3], it must be kept in mind that these are larger than the steps in the line-to-ground voltage $\Delta U_{\rm LE}$ (see, for example, Fig. 2(a), $\hat{U}_{\rm LL} > 2 \bullet U_{zk} \approx \Delta U_{\rm LE}$). Since the limits for the line-to-line voltage are higher, this results in reserves if one applies the limiting values indicated in Fig. 7(a) to the line-to-line voltage. It is not possible to state a universally valid limiting characteristic curve for the line-to-line voltage, since this is strongly dependent on the converter and the particular configuration of the drive system. However, there are substantial reserves in the range of rise times of some hundreds of nanoseconds, which is relevant for operation on a converter, compared to the former recommendations of DIN VDE/IEC [2]. These findings have lead to the publication of a new guideline by large European manufacturers of VSD's [9] and should be followed by standardization work of IEC and IEEE Committees working groups in the motors and drives field.

V. LIMITATIONS FOR THE INVERTER OPERATION OF INDUCTION MOTORS IMPOSED BY THE WINDING INSULATION

The comparison of voltages ΔU_{LE} which are possible in converter operation with limiting values for the maximum permissible voltages allow us to derive limits for the operation of induction motors in PWM inverter drives systems [7]. Fig. 8 shows at the top the possible voltages ΔU_{LE}, dependent on the voltage in the dc-link circuit. If the converter is located directly at the motor terminals, then $\Delta U_{\mathrm{LE}} = U_{zk}$. If the motor and the converter are connected via a relatively long motor cable, then there can be voltages ΔU_{LE} of up to two times the dc-link voltage U_{zk}. Experience has shown that the cable termination with the motor impedance reduces this value to approximately $1.7 \bullet U_{zk}$ in high-power drives systems [7]. In addition, the range of the maximum permissible voltages ΔU_{LE} is shown according to (2.3). Here, it was assumed that 40%–70% of the voltage step ΔU_{LE} drops off over the first coil ($\ddot{u}_t = 0.4 \cdots 0.7$; see Fig. 3), and that the voltage over the first coil immediately before a switching procedure U_0 is between 10%–15% of the intermediate circuit voltage (see Section II-B). This yields the ranges shown in the lower part of the figure. If the maximum occurring voltage ΔU_{LE} is smaller than the lower limit (lighter range), then a risky high stress of the winding insulation can be ruled out. If it must be expected that the voltage will be greater than the upper limit, then safe operation is impossible (dark range). The limiting characteristic of the individual motor can be found between these boundaries, and must be taken into account in the evaluation (grey area). For intermediate circuit voltages of 560 V, this leads to the following statements.

Motors with PD inception voltage of 600 V (turn insulation) can be operated on a pulse converter if either the winding design guarantees favorable voltage distribution, as was found to be the case, for example, with the 0.37-kW test motor, or if the pulse converter is connected practically directly to the motor terminals ($\Delta U_{\mathrm{LE}} = U_{zk}$). If the partial discharge inception voltage of the winding insulation is 900 V, an unacceptably high stress of the turn insulation is practically ruled out. During electrical deceleration or in the case of energy recovery via an active front-end increase of the dc-link voltage, up to about 115% of the nominal value may occur. Depending on the insulation system used, according to Fig. 8, these stages may or may not establish PD activity. This will not be continuous and less harmful as long as the stressing voltage falls back below the PD extinction voltage $U_e = 0,95 \cdots 1\, U_i$. Nevertheless, also for these applications, PD-free operation of low-voltage winding insulation including main and phase insulation [Fig. 7(b) and (c)] should be secured, because electrical aging of winding insulation may reduce PD inception and extinction voltages.

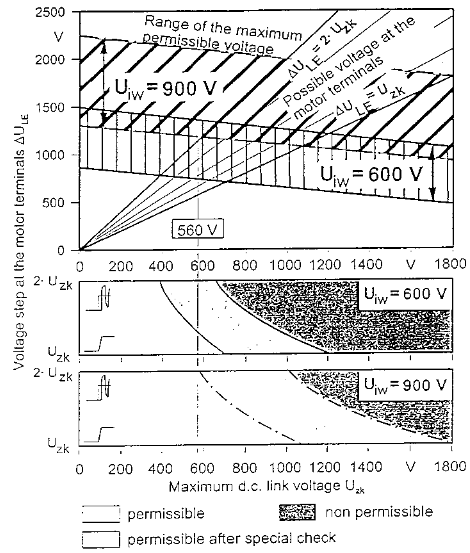

Fig. 8. Limit values of the terminal voltages of PWM-inverter-fed induction motors imposed by their winding insulation (hot spot temperature 155 °C).

VI. SUMMARY

Traveling waves on the cable between the converter and the motor can lead to transient jumps of the line-to-ground voltage on the motor side with amplitudes reaching twice the voltage of the dc-link circuit. Through the overlaying of oscillation processes in the winding with transient voltage distributions, under unfavorable circumstances, the voltage stressing the turn insulation can reach levels at which partial discharges occur in the air gap between adjacent wires. The partial discharges erode the wire enamel and, hence, lead to electrical aging of the winding insulation. Under these conditions, there is a close relationship between the partial discharge behavior and the failure behavior of the winding insulation. The winding insulation can, therefore, only be assured of having a sufficient lifetime if the electrical stress of main and turn insulation is always below the PD inception voltage.

On the basis of the knowledge about electrical stress and dielectric strength of the winding insulation, limiting values for the maximum permissible terminal voltage on asynchronous motors can be specified. It turns out that the earlier recommendations according to DIN VDE/IEC [2] contain great utilizable reserves. Substantial work has been done over the last years in order to define practical and physically based suggestions for the limitation of terminal voltages (as in the new draft of IEC 34-17).

Based on the results described above, recently, a new technical guideline has been issued by European producers of VSD's [9]. This GAMBICA/REMA publication defines two levels for the real voltage withstand capability of today's available motors in the European market, which are well above the first limiting values published previously. Level A covers the standard application in VSD's up to 500-V operating voltage. Level B requires an enhanced insulation system for supply voltages in the range 500–690 V, and it gives substantial information for the operation of 690-V machines. This activity of manufacturers should be followed by standardization work of IEC and IEEE Committees working groups in the motors and drives field, giving consumers, original equipment manufacturers, and producers substantial mandatory and binding rules for the application of VSD's.

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Martin Kaufhold (M'95) was born in Berlin, Germany, in 1964. He received the Ph.D. degree in electrical engineering from Dresden University of Technology, Dresden, Germany, in 1994.

While at Dresden University of Technology, he worked in the Institute for High Voltage and High Current Engineering in the field of high-voltage and diagnostic technologies, as well as machine insulation for converter technologies. From 1994 to 1996, he was a Postdoctoral Fellow and then a Research Officer with the National Research Council of Canada, where he was involved in projects involving high-voltage and dielectric diagnostics for energy transmission with HV-cable, GIS/GIL, and overhead power lines. Since 1996, he has been with Siemens AG, Berlin, Germany, working on the development of insulation, winding, and diagnostic technologies for large electrical machines with respect to modern concepts of ASD's. He is currently responsible for the development of large synchronous machines.

Herbert Auinger was born in 1940. He received the Dipl.Ing and Dr.Techn. degrees (technical science) from the Technical University of Graz, Graz, Austria.

Since 1962, he has been with the Automation and Drives Division, Siemens AG, Berlin, Germany, where he has held the positions of Development Project Manager, Chief Test Field Manager, Head of the Quality Assurance Department, and Director of Standards and Regulation Management. He is mainly involved in the development of electrical machines and converter/motor interfacing. He is the Chairman of the Technical Commission of the German Manufacturers Association Electric Drive Systems (ZVEI-TK 1/2), a Member of the Technical Board and Low Voltage Group of the European Committee of Manufacturers of Electrical Machines and Drives (CEMEP), and is associated with various IEC and DKE Standards Committees related to electrical drive systems and the safety of power electronic equipment.

Matthias Berth was born in Potsdam, Germany, in 1967. He received the Ph.D. degree in electrical engineering from Dresden University of Technology, Dresden, Germany, in 1997.

He is currently with the High Voltage Group, ABB Corporate Research Ltd., Baden, Switzerland.

Joachim Speck was born in Dresden, Germany, in 1951. He received the Ph.D. degree in electrical engineering from Dresden University of Technology, Dresden, Germany, in 1978.

Since 1974, he has been with the Institute for High Voltage and High Current Engineering, Dresden University of Technology. His research interests include field calculation, statistical evaluation, SF_6 insulation, and breakdown of solid dielectrics.

Martin Eberhardt was born in 1930. He received the Dr.-Ing. and Dr.-Ing. Habil. degrees from Dresden University of Technology, Dresden, Germany, in 1964 and 1981, respectively.

From 1971 until his retirement in 1995, he taught at Dresden University of Technology, where, from 1991 until 1995, he was the Head of the Institute for High Voltage and High Current Engineering. His research covered the insulation of electrical machines, polyethylene high-voltage cables, and high-voltage switchgear.