

Investigation on Parameters Influencing Turn-to-Turn Insulation Stress of Form-Wound Medium-Voltage Induction Machines

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Abstract—In this paper the influence of the voltage step on the turn-to-turn insulation is investigated when using silicon carbide (SiC)-MOSFET. As already known, the steep voltage gradient dv/dt by using of the modern inverter semiconductor devices leads to additional stress on the stator winding insulation system, especially the turn-to-turn insulation. The transient voltage distribution within the stator winding is measured to determine maximum stress on turn-to-turn insulation. Changing the values and distribution of the inter-turn capacitances it is possible to identify the influence of this parameter on the turn-to-turn insulation stress. Using the measurement results it is possible to define a maximum allowable voltage gradient in order to keep the turn-to-turn insulation within its specified safe operating range.

Keywords—voltage gradient (dv/dt); insulation; SiC - MOSFET

I. INTRODUCTION

The development of new semiconductor technologies such as silicon carbide SiC-MOSFET inverter, requires more scientific insights with respect to the electric machine's insulation system. The industrial application of this new technology is progressively increasing. Silicon carbide (SiC) has evolved in recent years to a promising future semiconductor material. The advantages are clear seen in industry e.g.: SiC is a wide-bandgap material, allows fast switching transitions, high switching frequencies and output voltages, but less losses. Future industrial SiC inverters are expected to produce output voltage changes five to ten times as high as current IGBT technology (in the range of $40\text{kV}/\mu\text{s}$ and more). However, these advanced properties also act accordingly to the insulation system of the connected electrical machine. Especially the fast voltage transition is causing stress on the stator winding insulation system as several studies show [1]-[2].

This research is supported by Austrian Research Promotion Agency (FFG) under the Bridge-program, grant no. 858502.

For the winding in electric machines, the higher switching speed means higher probability of partial discharge (PD) and thus a higher risk of insulation breakdown with significantly reduced lifetime. Currently it is not possible to predict accurately the lifetime of an insulation system, or the occurrence of a breakdown of the insulation. Test procedures like IEEE standard 1776-2008 apply a combination of thermal stress, vibration, humidity and electrical stress to the insulation, however the electrical stress is limited to low frequency sinusoidal supply. The test results are thus not applicable to predict future turn-to-turn insulation stress and lifetime.

The future problem of turn-to-turn insulation in combination with SiC technology is thus twofold. At first, the higher dv/dt rates of up to $40\text{kV}/\mu\text{s}$ and even more lead to higher transient overvoltage between adjacent turns especially close to the machine terminals. In addition to that, the steeper grades as well as increased switching rates have also influence on the inception voltage of partial discharge [8]. Partial discharge is identified as one dominant effect leading to aging of insulation systems. Though insulation materials resistant to partial discharge are available and applied, especially in medium voltage machines, the occurrence and intensity of PD activity needs to be kept as low as possible to keep reliability and lifetime high.

One additional point that needs to be considered is the fact that due to the aging process of the material during lifetime also the capacitance of the insulation system is changed. This change strongly depends on the material as well as manufacturing process used. This change of capacitance in turn influences the transient overvoltage distribution between single winding turns as will be shown, which may even further increase probability and intensity of PD activity thus progressively accelerating the destructive aging process.

Consequently, all industrial applications where high reliability and long product lifetime are obligatory, need to carefully weigh the advantages of evolving SiC technology with the risks associated with the insulation systems.

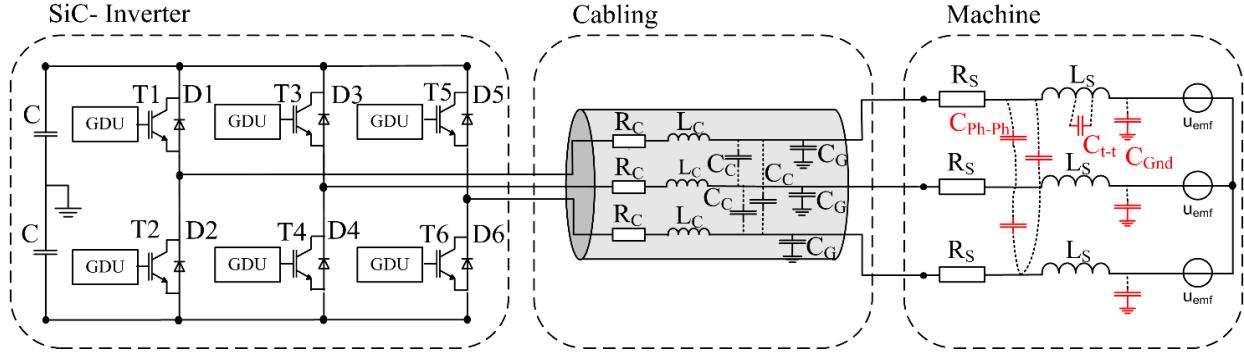


Fig 1. Electrical scheme of drive system with parasitic components

Based on this evidence, often the admissible switching speed of insulation systems needs to be restricted to avoid increased system cost through e.g. output filters.

The aim of this report is to investigate and understand the effect of a high voltage gradient (dv/dt) at the inverter output on the machines insulation system and resulting monitoring capabilities. Based on investigations on transient voltage distribution, current transient analyses, as well as accurate knowledge of the change of insulation material parameters during lifetime, monitoring of the stator insulation condition should be possible in future applications.

II. ELECTRICAL EQUIVALENT CIRCUIT OF TRACTION DRIVE AND MEASUREMENT PROCEDURE

A. Test bench setup

The main electrical components in modern traction drives are the inverter, cabling and machine, which, considering the high frequency and transient properties, form a complex network of resistances, inductances and capacitances (see Fig 1). As inverter, a voltage source inverter with SiC-MOSFET devices is used. Compared to today's typically applied industrial inverters based on IGBT technology, the SiC-MOSFET inverter offers the opportunity of significantly higher switching frequencies and faster switching operations [3]. Due to their faster switching transitions at the inverter output, which are several kV/μs higher than in case of IGBT technology, a steep voltage wave is generated, which causes an excitation of the complex system consisting of inverter, cable and machine.

The excitation by the inverter switching transition results in voltage wave reflection and further in transient oscillations of voltage and current signals immediately after the switching transition occurred. These transients are causing stress to several components of the system. For instance, the insulation material is stressed by the reflected incoming voltage wave at the machine terminal, due to the wave impedance mismatch between cabling system and machine, acting in extreme cases as an open line end, cf. [4] and [5]. Additionally, if the signal propagation time of the wave from the inverter to the machine is greater than the rise time of the inverter output voltage, the entire voltage wave is reflected at machine terminal. Thus, a critical cable length can be defined and in combination with a defined reflection coefficient, the overvoltage at machine terminal can be described by (1)-(3). Propagation time t_p is given in (1), with the quotient of the cable length l_c and voltage wave propagation velocity v_p defined by the cable parameters. Therefore, at a given voltage rise time t_r

determined by the inverter, a "critical length of the cabling to the machine" $l_{c,crit}$, can be defined such that $t_r = 2 t_p$.

$$t_p = \frac{l_c}{v_p} \quad \text{and} \quad v_p = \frac{1}{\sqrt{L'_C C'_C}} \quad (1)$$

$$t_r = 2t_p = 2 \cdot \frac{l_c}{v_p} \Rightarrow l_{c,crit} = \frac{v_p \cdot t_r}{2} \quad (2)$$

$$\Gamma_{ma} = \frac{Z_{ma} - Z_c}{Z_{ma} + Z_c} \quad (3)$$

In the case of the test and measurement setup in this investigations, the critical cable length has been exceeded due to a cable length of $l_c = 10$ m and a rise time of the inverter in a range $t_r < 50$ ns.

B. Measurement procedure

The principle of the measuring process is the excitation of the system by a voltage step with the inverter. As depicted in Fig 2 the maximum dv/dt of the SiC-half bridges for turn on respectively turn off is about 21kV/μs. It has to be noted that this typically is a rather low value compared to what will be possible with future SiC MOSFETs. The SiC-MOSFET modules used, are slowed down by the gate drive but still deliver faster switching transitions than typical IGBT modules. Using emerging module devices based on advanced package internal wiring, dv/dt rates of up to 40kV/μs and even beyond seem to be possible in future being of advantage for further reduction of switching loss.

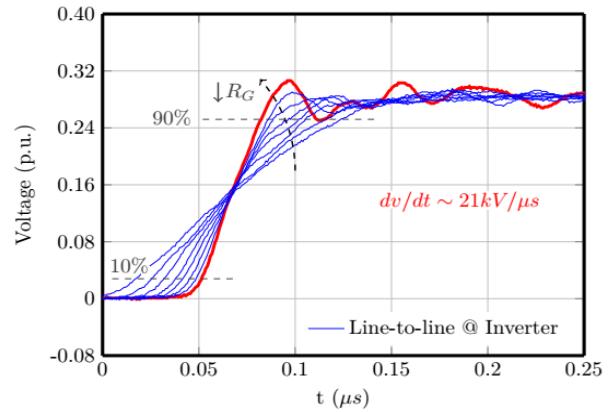


Fig 2. Inverter output voltage transient during active switching transition using low gate drive resistance.

A dv/dt at the inverter output of $21\text{kV}/\mu\text{s}$ is multiple times higher than the today's typical value of about $8\text{kV}/\mu\text{s}$, reached by IGBT-based train propulsion systems. A decrease of the dv/dt value down to $2\text{kV}/\mu\text{s}$ is possible for the implemented SiC-inverter by modifying the gate drive unit, cf. Fig 3.

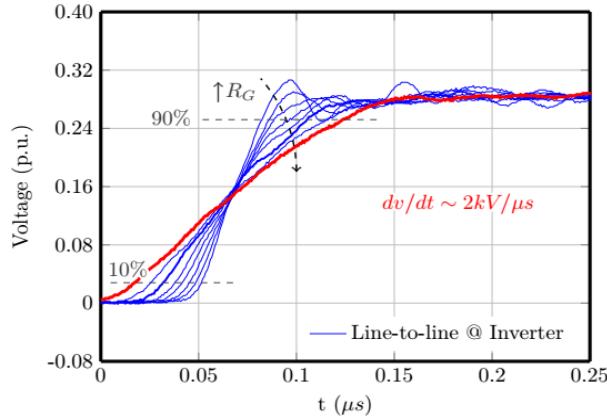


Fig 3. Inverter output voltage transient during active switching transition using high gate drive resistance.

For all further measurements in this investigation, the dv/dt inverter output voltage rate is defined with $21\text{kV}/\mu\text{s}$. However, the influence of the parameter dv/dt respectively t_r should be clear due to the previously discussed relationships. In order not to stress the insulation of the machine in addition to the fast dv/dt with voltage levels at rated dc-link supply, the investigations are performed with reduced dc-link voltage values. As can be seen in Fig 2 and Fig 3, the measurements are carried out with a dc-link voltage of 0.25 of the nominal value (per-unit system). With a constant factor, the measurements are finally recalculated to the actual values.

Voltage and current transients are measured after step excitation by the inverter at a 1.4 MW induction machine with form-wound stator coils. The machine is a traction motor for railway applications and was especially manufactured with tapped stator windings. The stator winding consists of several coils per phase connected in series and each coil consists of a defined number of turns. The first coil, second coil and last coil of one phase are completely equipped with taps, which facilitates the measurement of the voltage at different locations within the coils. Due to the wye connected windings scheme, the neutral point is available at the last position of the last coil. Thus, it is possible to measure the voltage between different turns, between turns and neutral point, and between turns and the grounded machine housing to investigate the transient voltage distribution and its dependence on various parameters, e.g. inverter output voltage rate.

Fig 4 (a) depicts the voltage overshoot at the machine terminal measured against the machine housing, representing the voltage drop across the main groundwall insulation of the winding system. The voltage trace denoted with 'L1-inverter' shows the measurement at inverter output, the trace denoted with 'L1-6' was measured at machine terminal and 'L1-8' and 'L1-11' representing measurements at winding taps of the first coil after the machine terminal. The voltage with respect to the machine housing at the machine terminal 'L1-6' is higher than at position 'L1-11', with about 40% above the steady state value. Obviously, the voltage overshoot is decreasing towards the neutral point, which is in accordance with literature.

For the insulation of the machine this means, that the high dc link voltages of traction drives require a substantial groundwall insulation. The highest voltage occurs over the main groundwall insulation at coils connected to the machine terminal in contrast to coils near the neutral which are significantly less stressed by the voltage to ground. With 'sufficient' thickness of the main ground wall insulation, an early failure due to insulation breakdown of this insulation caused by aging is less probable.

The following Fig 4 (b) depicts the voltage distribution of one coil and several selected turn-to-turn voltages of the same coil. The voltage across a coil is measured before the first turn and after the last turn. The steady state voltage after the transient oscillation has decayed is reached at about $2\mu\text{s}$ after the switching transition of the inverter.

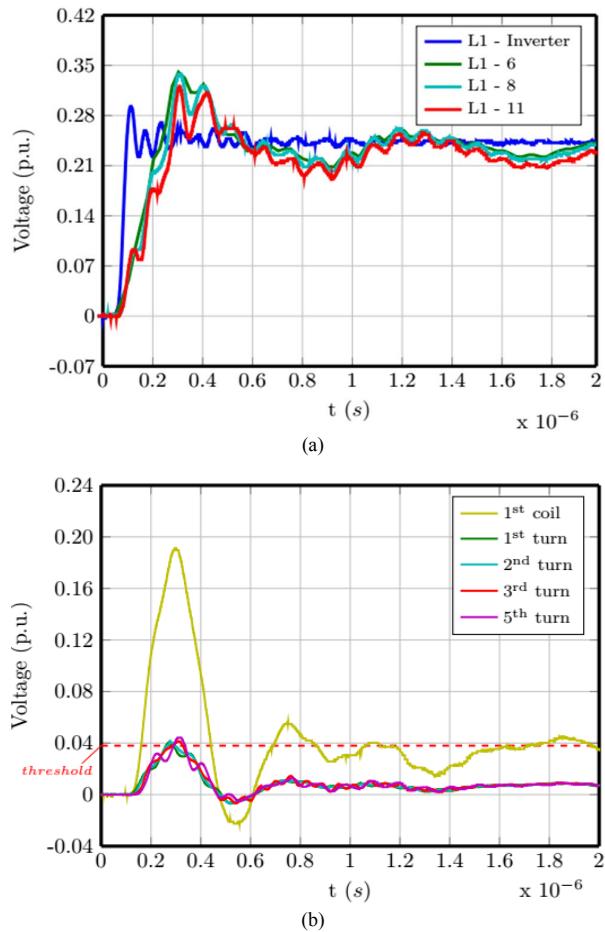


Fig 4. Measurement of (a) voltages at first coil close to machine terminal with respect to machine housing and (b) coil and turn-to-turn voltages of the first coil of phase L1.

In this case the stress to the turn-to-turn insulation is observable. The turn-to-turn insulation is most important for the machine design process and the manufacture of insulation materials. There are more restrictions at the design of the turn-to-turn insulation, due to the geometrical design of the slots and conductors. With high voltage peak values and gradients between single turns of a coil, caused by the nonlinear voltage distribution at inverter-fed drives with steep voltage output rates, partial discharge (PD) may occur over the turn-insulation. The turn-insulation typically consists of thin tapes. Therefore, presence of PDs is acting on the relatively thin

insulation leading to significant aging and gradually will erode a hole through the insulation in a relative short time during operation. This will happen once the thresholds of PD inception are exceeded. This leads to a sudden turn-to-turn fault and due to the high internal short circuit currents consequently to more and more affected parts that finally leads to a ground fault due local thermal overheating.

The occurring peak voltages in Fig 6 at the beginning of the oscillation at every turn exceed the threshold for the maximum allowed turn-to-turn voltage defined by the insulation manufacturer. Thus, the setup with the SiC-inverter combined with the cable length of 10m and the selected machine would operate above maximum allowed values in case of rated dc-link voltage. In Fig 5 the influence of the overvoltage and the switching transition (dv/dt) is shown for a separated setup. The value of 0,04 in Fig 5 results from scaling the threshold based to the lower dc link voltage used as mentioned above. Thus, during the measurements taken in this investigation, the insulation was not stressed above the rated values. Otherwise, significant aging as well as destruction of the insulation material during the investigation was possible.

C. Influence of switching parameters and stimulated changes of parasitic turn-to-turn insulation capacity

To show the influence of inverter switching parameters on the turn-to-turn insulation stress, in Fig 5 the relationship between the overvoltage of the first coil third turn and the dv/dt at the inverter output is depicted. The thin and delicate turn-to-turn insulation has maximum allowed voltage of 0,04 p.u.. As can be seen, the peak value of a single turn voltage is increased with the switching speed. In this case, the critical value is exceeded when applying a voltage step with a switching speed dv/dt value above $\sim 13\text{kV}/\mu\text{s}$.

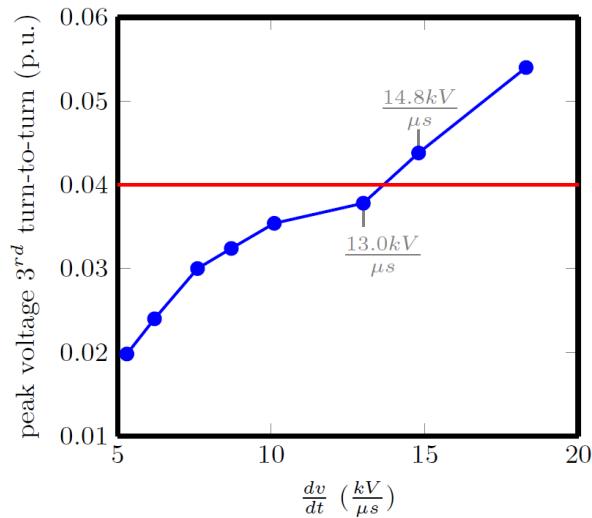


Fig 5. Relationship between turn-to-turn overvoltage at first coil, third turn and dv/dt inverter output.

Fig 6 depicts the comparison of the turn-to-turn voltage of the first turn in case of the initial machine state (blue trace) and in case of a change of the parasitic capacitance C_{t-t} (red trace) by placing a capacitor parallel to another turn (cf. C_{t-t} in Fig 1). A capacitor was connected to the taps of the respective turn. The turn-to-turn voltage was measured with an active differential probe and recorded by use of an oscilloscope.

Obviously, the change of the parasitic capacitance also influences the voltage and current transients inside the machine winding, in the depicted case resulting in lower voltage overshoot (k_{ov}). These parasitic capacitances are influenced by the insulation health state, cf. [6]. This in turn means that a change in the insulation health state, influences the relation between the impedance of the cable and machine Z_c respectively Z_{Ma} . As a result, the occurring overvoltage as well as frequency components in the transient part will also change during the aging process of the insulation.

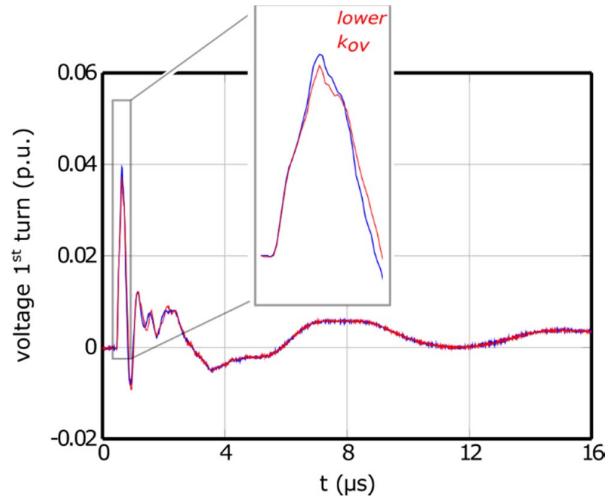


Fig 6. Influence of changed parasitic capacitances on turn-to-turn voltages. (without change (blue); with additional capacitance value (red)).

Considering the capacitance of the insulation material several studies confirm a reduction of the capacitance values especially when performing thermal stress during aging cycles [9], [10], [11]. Looking at Fig 6 a capacitance increase due to additional external capacitor is leading to a reduction of the transient voltage overshoot (k_{ov}). Thus a reduction of material capacitance during lifetime might as well increase transient voltage overshoot putting additional stress to the turn-to-turn insulation.

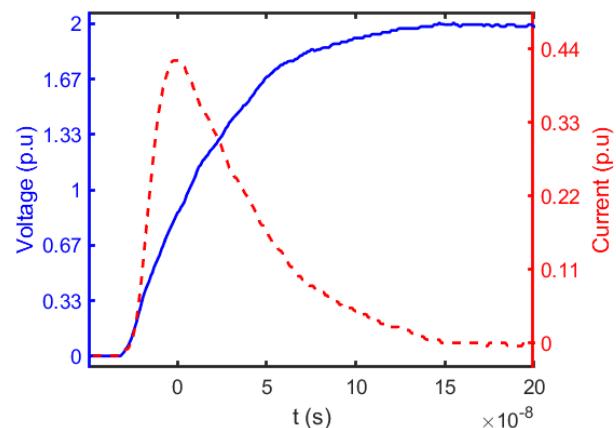


Fig 7. Pulse voltage (blue, solid) applied to insulation material and resulting current capacitive current (red, dashed) to determine influence of pulse voltage stress.

When looking at the stress that high dv/dt and high voltage levels are putting to the material, a similar trend can be observed. This is shown in Fig 7, which shows a sample of the

measured voltage applied to an insulation material (blue, solid trace) and the resulting current measured (red, dashed trace). Based on these measurements, the capacitance of the material can be estimated and its change traced during the repetitive pulse voltage stress test.

This trend is depicted schematically in Fig 8. As can be seen, the material capacity decreases from its initial changes value as soon as significant pulse voltage stress is applied. This trend shows good agreement with results obtained by other investigations and other types of ambient stress, like especially thermal e.g. [12].

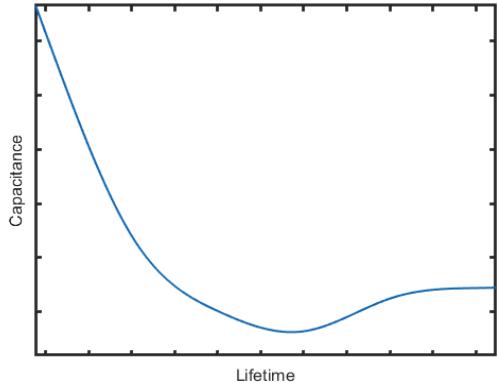


Fig 8. Schematic estimation of capacitance change during lifetime of the material, calculated during pulse voltage aging.

To investigate the influence of the changing turn-to-turn insulation capacitance on the local distribution of the transient overvoltage, capacitor was connected to the winding taps at different positions. It has to be mentioned, that by connecting external capacitors to winding turns, parasitic capacitance can only be increased what is the opposite of the trend taking place during pulse aging and in addition also a slight change of inductance/resistance is introduced due to the additional wiring. Nevertheless the results show, what effects can be initiated by the aging of the insulation.

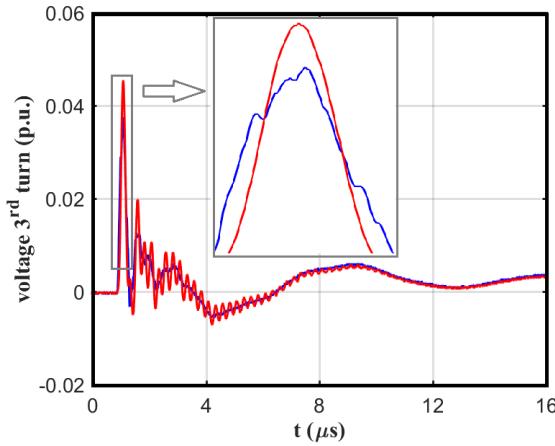


Fig 9. Change of internal pulse voltage distribution (3rd turn) due to stimulated modification of turn-to-turn capacitance at 3rd turn.

When comparing the results of the following Fig 9 with that of Fig 6 it is obvious, that by increasing turn-to-turn capacitances at different places along the winding, both an increase of the maximum transient overvoltage as well as a decrease can be initiated along the different turns. For the

overall turn-to-turn insulation this means, that aging induced capacitance changes can lead to both a reduction as well as an increase of insulation stress. When considering boundary conditions for product lifetime estimations, one main topic is to limit the maximum turn-to-turn voltage well below a critical threshold to avoid e.g. partial discharge to develop. When considering the distribution of the transient overvoltage along the turns, it may eventually happen, that a change in the material capacitance, induced by various kinds of stresses (e.g. thermal) also lead to a significant change of a single turns transient overvoltage. This in turn can trigger an additional stress mechanism caused by partial discharge activity in the material leading to erosion and thus further accelerating the aging process.

III. CONCLUSION

In this paper, electrical pulse voltage stress applied to electric machines turn-to-turn insulation is investigated. All measurements in this investigation were done on form wound stator windings of medium voltage insulation system. It was shown that, based on measurement of the turn-to-turn voltage it is possible to define a maximum allowable dv/dt value for a given configuration of insulation system as well as cable length. Generally spoken, the qualitative conclusions drawn from the obtained results can be expected for other form-wound squirrel cage induction machines with same insulation system and similar power/voltage rating. However, regarding quantitative conclusions a comparison of more machines within a series seems to be necessary due to the random distribution of the inter-turn capacitances.

In addition it was also shown, that the distribution of parasitic capacitance along the winding also influences the maximum occurring turn-to-turn overvoltage. During lifetime and thermal stress a reduction of parasitic capacitance will be initiated which in turn may at a specific point trigger unwanted PD activity, further accelerating aging of the material. This aging induced capacitance change and its influence on the turn-to-turn insulation stress should thus also be considered when defining maximum allowable dv/dt values for specific applications.

ACKNOWLEDGMENT

The authors want to thank Bombardier Transportation-Rolling Stock Equipment (RoQ), especially Mr. H. Mannsbart (global head of BT_RoQ_Mechanical) as well as ISOVOLTA AG, especially Mr. A. Schindler (member of the executive board) for research/development funding and project supervision. Special thanks for his generous support and technical feedbacks goes to Mr. M.Bazant (Bombardier Transportation_head of global BT_RoQ_M_Drives Product Developm. & Mgmt) and Mr. Werner Grubelnik (Isovolta AG_ProductMgmt.Energy-High Voltage). Furthermore the authors want to thank colleagues from Bombardier Transportation BT_RoQ (Dr. N. Weyrich and Mr. Edgar Moser), Isovolta AG/Austria (Dr. I. Bergmann & Mr. R. Fasching) as well as TU-Vienna (Prof. Dr. H. Ertl & Mr. Th. Fuchsleger) for all their feedback. The authors further are very indebted to LEM-Corp. (especially Mr. A. Hürlimann/Chairman of Board of Directors, Dr. W. Teppan & Mr. J. Burk) for the cooperation and generous support.

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