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MODELING OF THE ELECTRIC FIELD GRADING AT CONDUCTOR-DIELECTRIC INTERFACES UNDER FAST RISE TIME PULSES

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Abstract: The insulation systems are subjected to different exploitation stresses. There are electrical stresses due to the time dependence and spatial distribution of the electric field. A differentiation has to be made between sinusoidal (power network) and pulsed stresses. In spite of the overvoltages (lightning and switching) they are also a result of power converters. The power converters technology leads to different and higher electrical stresses in machine windings insulation and cable terminations. Then the interfaces in insulation systems generally consist of combination of conducting, semiconducting and insulation materials adjacent to each other. A criterion for the electrical stresses in insulation systems are partial discharges which occur at these interfaces. The effectiveness of stress-grading systems under fast rise time pulses is discussed in the article. Simulations using Finite Element Method are presented.

Keywords: electric field grading, modeling, electric machines.

1. INTRODUCTION

The introduction and rapid development of Variable Speed Drives (VSD) had a significant impact on the electrical motors supply voltage as well as on the machine winding insulation system. In those drives the control unit is based on pulse width modulated (PWM) train of pulses with slew rate up to 100kV/μs and frequency repetition up to 100kHz [1]. These fast pulses impose high electric and thermal stresses on the end portion of the motor winding what in effect could lead to initiation of partial discharges and gradual degradation of machine winding insulation. Therefore the traditional stress grading system in medium voltage motors, based on field-dependent material is not effective when the motor is fed from PWM converter [2,3].

Conventional stress grading system of the motor winding end consists of layer of conductive armor coating applied on the groundwall insulation (Fig.1) [4]. Depending on the nominal voltage level and design of the winding insulation, the conductive armor tape may be terminated by additional layer of semiconductive stress grading coating. These layers are introduced into the insulation in order to linearize the potential distribution along the groundwall insulation surface [2-4].

At power frequency (50 Hz) the conventional stress grading system works well, but exposure to PWM voltage source converter can lead to premature stator winding failure. This is due to the fast rise time (high *dU/dt*) and repetition rate of the PWM voltage waveform what result in enhanced electric field strength and development of hot spots in the stress grading coatings [2,3,5].

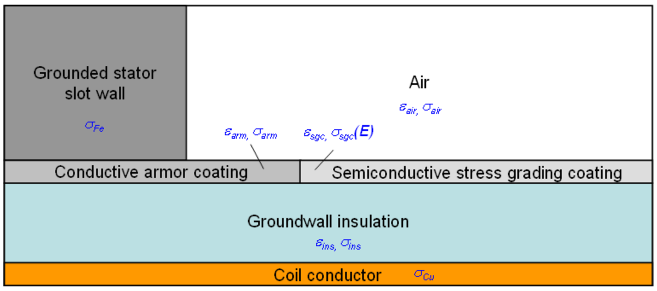

Fig. 1. Cross-section of a typical form-wound coil with conductive armor and semiconductive stress grading coatings (σ_x, ε_x - electrical conductivity and permittivity of materials used)

As described in [5], under power frequency the electric stress is dissipated in the semiconductive grading tape. This is shown in Figure 3a by the heat generated in the portion of semiconductive stress grading system. Under fast rise time pulses generated by PWM converter, the electrical conductivity of the armor coating is too low to keep the electric stress in the semiconductive stress grading tape (away from the stator slot). Thus the high stress is moved to the end of the slot as presented in Figure 3b. As a result, partial discharges and additional Joule heating may damage coating in this area [2,3,5].

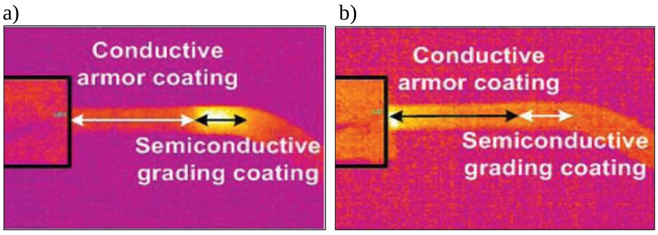

Fig. 3. Thermographs of heat generated in the stress grading system of a coil end under AC (a) and pulsed (b) voltages [2]

One of the methods to overcome this problem is to modify the conventional stress grading system by increasing the electrical conductivity of the armor tape so as to keep the stress in the semiconductive grading coating. Thanks to the nonlinear and field dependent σ vs E characteristic, the semiconductive stress grading coating is able to modulate the electric field below a certain value. Then, the electric stress and the Joule heating can be distributed over a larger extent. It could be said that such a stress grading system works as a natural filter that divide the heat and electric stress into a low and high frequency components [2,3,5].

In this work the problem of effectiveness of stress grading system under power frequency (50Hz) and fast rise time pulses is discussed. Transient FEM simulation results of electric field distribution in the end portion of the motor winding insulation are presented.

2. FEM SIMULATIONS

2.1. Simulation approach

The simulations of the electric field grading effectiveness in the end portion of typical 6kV motor coil have been done by means of COMSOL Multiphysics v4.3b. A transient 2D, coupled circuit-field model was created using the *Electric Circuit* and the *Electric Currents* program interfaces available under COMSOL AC/DC Module. The pulse type voltage source was used in the *Electric Circuit* interface as the model excitation. The real PWM fast rise time impulse waveforms may include overshoots and oscillation components as presented in Figure 4, but in this case, the simplified approach has been used.

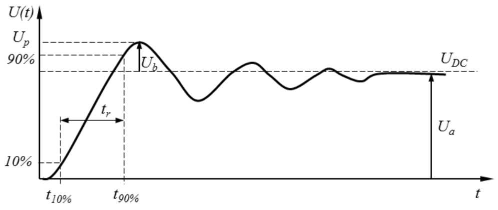

Fig. 4. Typical PWM impulse waveform with overvoltages

The PWM impulse was modeled with a wave of trapezoidal impulse (Fig. 5) with the following parameters: rise time t_r=50ns, fall time t_f=50ns, pulse width t_w=2.5μs and period T=3μs.

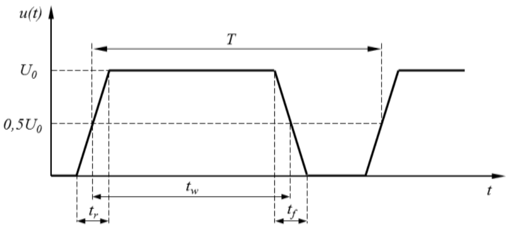

Fig. 5. Typical trapezoidal impulse waveform and its parameters

The external circuit with pulse voltage source was connected to the FEM model through a special program feature. Then the equation (1) was solved in every point in space in order to obtain electric potential distribution. The electric field distribution was then calculated using the following expression: $E = -\nabla V$ [6].

$$-\nabla \cdot \frac{\partial}{\partial t}\big((\varepsilon_0 \varepsilon_r \nabla V) - \nabla \cdot (\sigma \nabla V)\big) = 0 \qquad (1)$$

where: ε_0, ε_r – absolute and relative permittivity, V – electric potential, σ – electrical conductivity.

2.2. Model details

The geometry model of the end portion of the stator winding used for transient FEM simulations is presented in Figure 1. The model consists of copper conductor, grounded stator slot, 4mm thick groundwall insulation and conductive armor and semiconductive stress grading coatings (both of 0.5mm thickness). The properties of materials used in analysis are presented in Table 1.

Table 1. Material properties used in simulations

Material / Parameter	Relative permittivity ε_r	Electrical conductivity σ [S/m]
Copper conductor	1	$5.9 \cdot 10^7$
Iron	1	10^7
Groundwall insulation (4mm)	4	10^{-12}
Armor coating (0.5mm)	2	$5 \cdot 10^{-3}$
Stress grading coating (0.5mm)	16	$\sigma(E)$

The electrical conductivity of the armor coating is constant in this analysis, but the conductivity of the semiconductive stress grading coating is an exponential function of electric field E. The nonlinear field dependent conductivity of the stress grading coating is governed by the equation (2) in which the coefficients: σ_0, k and n depend on material properties. In this case the parameters of SiC stress grading tape has been used [7].

$$\sigma(E) = \sigma_0 \exp(k\,|E|^n) \qquad (2)$$

where: $\sigma(E)$ – nonlinear field dependent electrical conductivity, σ_0 – initial electrical conductivity of material (σ_0=5.9e^{-9} S/m), k, n – factors dependent on material properties (k=3.4, n=0,6), $|E|$ - absolute value of electric field strength [7].

3. SIMULATION RESULTS AND DISCUSSION

At first an electric field distribution and equipotential lines in a typical form-wound coil configuration with conductive armor and semiconductive stress grading coatings under power frequency (50Hz) are presented (Fig.6). Both the stress grading coatings are applied to groundwall insulation in order to suppress partial discharges on the end portion of the machine winding. The electric field distribution depends not only on the permittivity of dielectric materials, but also on the conductivity of surface.

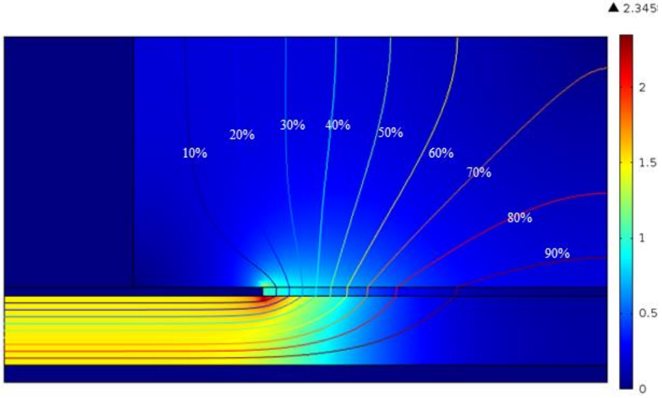

Fig. 6. Electric field distribution and equipotential lines in the end portion of machine winding under AC power frequency voltage

At power frequency supply voltage the conductive armor tape acts as a grounded screen as can be seen in the Figure 6. It could be concluded that in a low frequency range, the considered field grading system is effective because the maximum electric field strength is moved away from the critical stator slot area (near a triple point).

Then, the behavior of the considered stress grading system under trapezoidal fast rise time pulse voltage has been analyzed. The electric field distribution and equipotential lines plots are presented in Figure 7 for selected times *t* (50ns, 250ns, 1µs and 1.5µs).

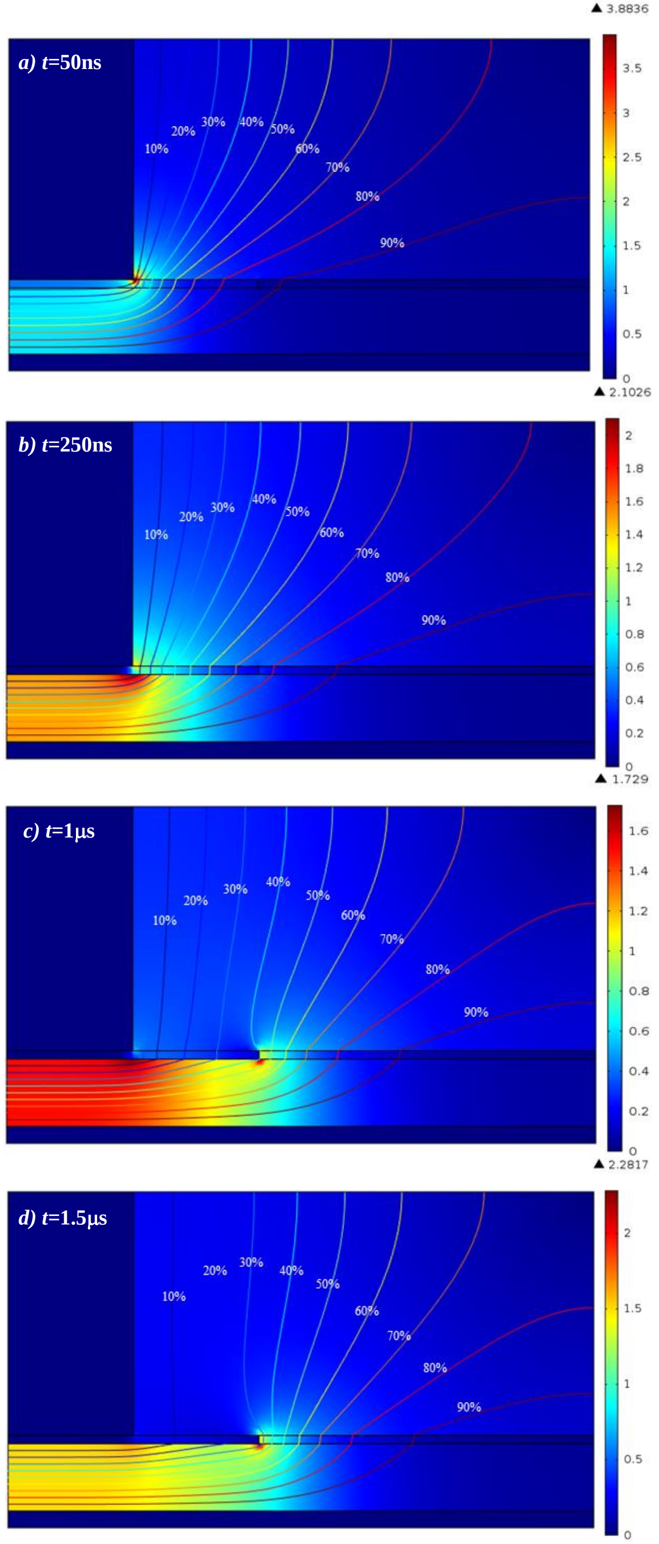

Fig. 7. Electric field distribution and equipotential lines in the end portion of machine winding under pulse voltage for specific times: a) 50ns, b) 250ns, c) 1µs, d) 1.5µs

As can be seen in Figure 7, the electric field distribution in the end portion of machine winding under fast pulse, changes significantly over the time. During the rise time of the pulse the maximum electric stress occur at the slot exit, near the triple point. In this case the conductive armor coating is not effective as a grounded screen. If the maximum electric field strength is on the level of inception of partial discharges, it could trigger degradation process of the groundwall insulation [8].

Over time, the maximum stress is moved from the slot exit toward the coil end. Analyzing the maximum electric field strength in the insulation for the considered times, it could be concluded that firstly, the maximum field strength decreases from 3.9kV/mm at *t*=50ns up to 1.73kV/mm at *t*=1µs and then rises to almost 2.3kV/mm at *t*=1.5µs (similar value as for power frequency voltage). At the last considered time *t*=1.5µs the high stress is localized beyond the slot exit, at the border between conductive armor tape and semiconductive stress grading coating of field dependent conductivity. The distribution of potential *V* and electric field strength *E*, along the groundwall insulation surface, vary with time. The changes in *E* and *V* distribution could be seen in Figure 8.

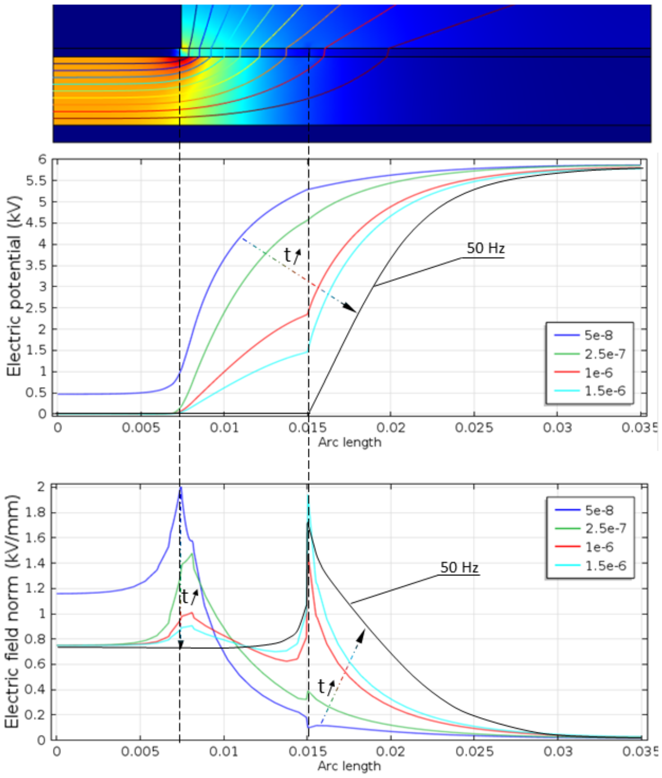

Fig. 8. Electric potential (a) and electric field distribution (b) along the groundwall insulation surface for specific times

At time *t*=50ns and 250ns the highest electric potential gradient is localized near the slot exit, but at times *t*=1µs and 1.5µs is moved to the border between the armor and the stress grading coatings. It could be concluded that over the time the electric potential distribution along the insulation surface become more and more close to the 50Hz distribution (when the armor coating acts as grounded screen). Analogical situation could be observed in the electric field distribution plot in Figure 8.

Based on presented simulation results of electric field distribution in the end portion of motor winding, it could be concluded that the highest electrical stresses occur during the rise time of the pulse. However, in this case the simplified situation with trapezoidal pulse waveform has been considered. In real PWM fed motor, the problem is much more important due to overshoots and oscillations appearing in the voltage waveform. Then the maximum values of the electric field strength could be higher and much more dangerous to the machine insulation system.

4. CONCLUSIONS

In this article the effectiveness of electric stress grading system in the machine winding insulation, under power frequency and fast rise time pulse voltages was discussed. The analysis was based on FEM simulations by means of COMSOL Multiphysics.

The analysis showed that the problem of high electric stress occurring near the slot end under pulse voltages is of high importance. The electrical and thermal stresses could lead to the gradual degradation of the machine winding insulation system. The problem is much more dangerous when overshoots and oscillation components exist in the voltage waveform.

The problem was discussed based on example of machine winding insulation system but analogous situation relate also to cable terminations.

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MODELOWANIE ROZKŁADU POLA ELEKTRYCZNEGO NA POWIERZCHNIACH GRANICZNYCH METAL-DIELEKTRYK PRZY WYMUSZENIACH IMPULSOWYCH

Key-words: układy izolacyjne, sterowanie rozkładem pola elektrycznego, modelowanie, maszyny elektryczne

Narażenia eksploatacyjne urządzeń elektrycznych są przyczyną degradacji ich układów izolacyjnych, przy czym intensywność i dynamika tych procesów zależą od poziomu natężenia pola elektrycznego, jego przebiegu czasowego i częstotliwości. W grupie narażeń szybkozmiennych szczególne znaczenie mają przepięcia impulsowe, oddziaływujące na układy izolacyjne maszyn elektrycznych, gdy stosowane jest sterowanie z modulacją szerokości impulsów zasilania. Narażenia napięciowe w układach przekształtnikowych stanowią ciągi szybkich impulsów przełączających, formułujących powtarzalne sekwencje, charakteryzujące się modulowaną szerokością i krótkimi czasami narastania i opadania zboczy. Takie warunki mają zasadnicze znaczenie dla powstawania i rozwoju wyładowań niezupełnych w układach izolacyjnych maszyn elektrycznych i kabli elektroenergetycznych.

Problem ten dotyczy między innymi elementów układów izolacyjnych tworzących tzw. punkt potrójny (ang. *tripple point*), a więc wyprowadzeń uzwojeń ze stojana maszyn elektrycznych oraz głowic kablowych, w których natężenie pola elektrycznego może osiągać wartości przekraczające natężenie początkowe wyładowań niezupełnych. Stosowane jest wówczas sterowanie pola elektrycznego przez zastosowanie kombinacji materiałów przewodzących, półprzewodzących i izolacyjnych. Kryterium projektowania tego typu układów izolacyjnych jest między innymi wartość natężenia pola elektrycznego.

Artykuł dotyczy problemu efektywności sterowania rozkładem pola elektrycznego w warunkach narażeń szybkozmiennych podczas oddziaływania napięcia impulsowego o krótkim czasie narastania. Przedstawiono wyniki symulacji komputerowych rozkładu pola elektrycznego w układzie modelowym elementu izolacji uzwojenia maszyny elektrycznej z zastosowaniem metody elementów skończonych, w odniesieniu do narażeń sinusoidalnych i narażeń impulsowych.