Effects of Microvaristors in the Insulation of Inverter Fed Drives

S. Blatt[1*], V. Hinrichsen[1]
[1]TU Darmstadt ,FG Hochspannungstechnik, Landgraf-Georg-Str. 4, Germany

*Email: <blatt@hst.tu-darmstadt.de>

Abstract: In this work the possible effects of microvaristors in the insulation of inverter fed drives are investigated. The insulation of electrical machines is stressed by overvoltages caused by traveling wave effects, resulting from the short rise time of the inverter voltage, the length of the cable between inverter and electrical drive and as well from the mismatched end of the cable at the machine terminals. Due to the high pulse frequency of the inverter, such overvoltages occur several thousand times per second. In the long term, the machine insulation is thus degrading by partial discharges caused by these overvoltages. In former research it has been shown that external metal-oxide varistors connected directly to the machine terminals help to reduce steepness as well as amplitude of the overvoltages, resulting in lower interturn voltages in the machine. Since the year 2000, micro-varistors are available on the market, used so far for field grading systems of cable accessories. Also, some further novel applications are being investigated and have been reported.

For this contribution the effect and behavior of microvaristors in the insulation of the electrical machine has been analyzed. The idea is to distribute the electrical characteristics of external overvoltage protection and steepness reduction directly in the machine insulation. Simulation results show an improved voltage distribution in the windings due to the effects of microvaristors. On the other hand, the nonlinear voltage-current-characteristic of the micro-varistors leads to increased resistive current and subsequently power losses in the electrical machine. An optimum has therefore to be determined by simulations as well as by experimental investigations. This is particularly difficult as for instance the voltage-current-characteristic of the material is not specified for such high-frequency applications. It has to be measured and modeled for the simulation. Parameters that can be varied by the manufacturing process of the micro-varistors are the non-linearity of the material and the "switching point" (i.e. the field strength where the material becomes dominantly resistive).

1 INTRODUCTION

Microvaristors consist of doped and sintered zinc oxide, similar to MO varistors. They have a grain size of approximately (10…200) micrometers and a nonlinear voltage-current or field strength-current density characteristic. An example of a non linear *E–J* characteristic is shown in **Figure 1**. The electrical behavior of a microvaristor filled insulation material is usually shown in an *E–J* characteristic for better comparison of different materials.

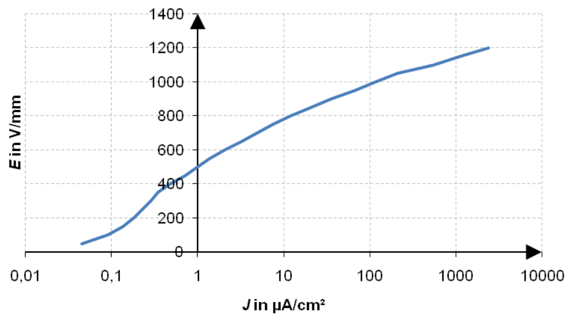

Figure 1: Example of a nonlinear *E–J* characteristic with a switching point of 500 V/mm

The *E–J* characteristic can be divided into three regions. The first region is denominated as leakage current region. In this region current density is very low and an increase of field strength results in a nearly linear increase of current density. The grain boundaries of the ZnO grains prevent a larger current flow. The second region is called breakdown region, in which current density is nonlinearily dependant on field strength due to break-down of the grain boundaries. This means that even a moderate increase of the field strength causes a huge increase of current density. In the third region, called high current region, current density becomes more linear again and is governed by the conductivity of the ZnO grains. When using microvaristors as filler in a polymeric insulation material, this non-linear behaviour is partly transferred to the polymer. The resulting *E–J* characteristic of the filled insulation material can be adjusted by variation of the grain size as well as by the filling degree. The "switching point" is defined as the electric field strength, at which the current density reaches a value of 1 µA/cm². Due to the high permittivity ($\varepsilon_r = 300...1000$) of microvaristors the compound has also a higher capacitance.

2 INVERTER FED DRIVES

More and more electrical motors are fed by inverters, due to the advantage of operating at variable speeds. Often, motor and inverter are separated and linked by a long cable, which can easily exceed a length of 100 meters. The inverter output voltage is a rectangular pulse train of several thousand Hertz pulse frequency, each impulse having a rise time of some 100 ns. Due to these reasons and the miss-matched end of the inverter-cable-motor configuration, traveling wave effects will cause in worst case doubling of the voltage at the machine terminals. These overvoltages occur several thousand times per second because of the high pulse frequency (**Figure 2**).

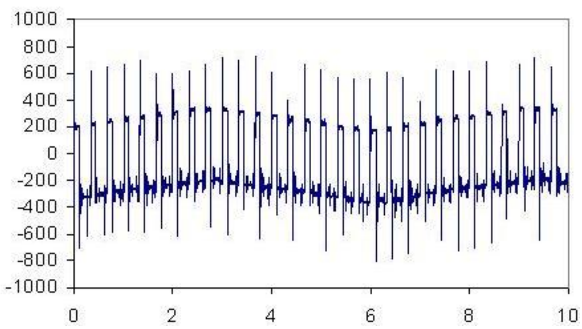

Figure 2: Overvoltage at the machine terminals [2]

Such overvoltages cause partial discharges in the machine insulation, leading to deterioration and, in the long term, finally to an insulation breakdown. **Figure 3** shows the voltage distribution within an inverter fed machine. It is observable that the voltage from the first coils to ground (U_{C1} to U_{C3}) are much higher than the voltage of the dc link circuit (U_Z). At the machine terminals, up to 2 p.u. overvoltage can be observed.

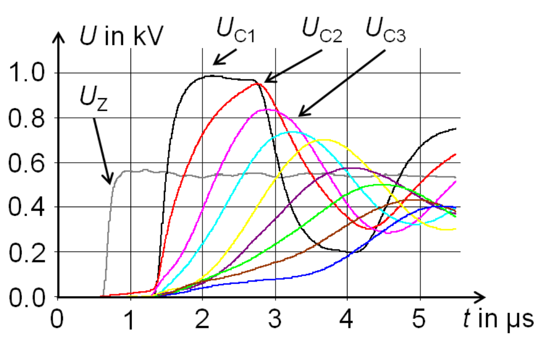

Figure 3: Measured voltage distribution of a 7.5 kW inverter fed motor [2]

A possible approach to limit these overvoltages is to introduce microvaristors to the insulation of the inverter fed drive. Former investigations with specially dimensioned MO varistors connected to the machine terminals have proven that the overvoltages can be limited due to the high capacitance of the MO varistors and due to their non-linear voltage-current characteristic [3] [4] [5] [6] [7]. Now, the effect of microvaristors distributed in the machine insulation has been investigated and will be reported in the following.

3 MODEL OF THE MACHINE

3.1 Model without microvaristors

For simulating the voltage distribution a model of the machine winding with passive elements is needed. This model is taken from [1]. The winding is divided into eight coils, and each coil is divided into 17 turns. Each turn is modeled by a ladder circuit [1] shown in **Figure 4**.

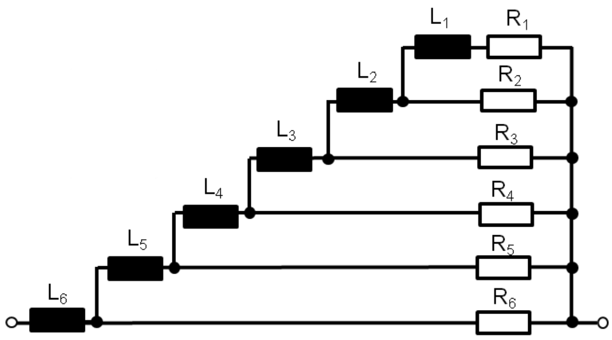

Figure 4: Ladder circuit of one turn [1].

Application of the ladder circuit is necessary to cover the skin effect. The values of the resistances and inductances are also taken from [1]. **Figure 5** shows a segment of the simulation model. The RL_i and C_{Ti} elements are the ladder circuit and spatial capacitances between adjacent turns, respectively. Capacitances, which are not neighbored in the equivalent circuit, are connected by the interconnection points A_i.

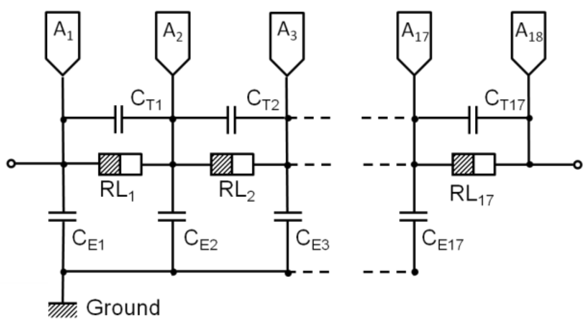

Figure 5: Segment of the simulation model

Furthermore, capacitances between the wires and the stator, i.e. ground, must also be modeled. Compared to the distance between two wires, the distance between wires and stator are larger. Therefore, values of C_{Ei} are around ten times smaller than those of C_{Ti}. The values of C_{Ei} and C_{Ti} were determined by FEM simulations [1], where the relative permittivity of the insulation was set to a value of ε_r = 2. Comparing the results of the transient analysis with the measurements presented in [2] shows that simulated and measured voltage distributions do not match exactly. The simulation can be improved by using a permittivity of ε_r = 4.

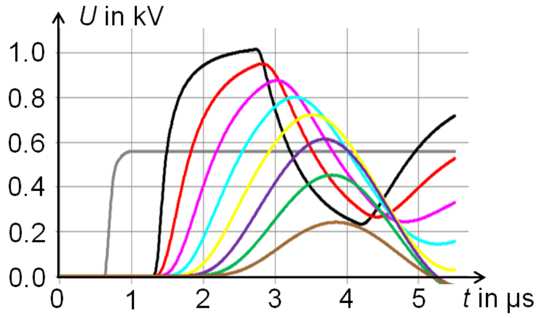

Figure 7: Simulated voltage distribution of the 7.5 kW motor with ε_r = 4.

The final simulation result, presented in **Figure 7**, shows only few differences of the voltages from wires to ground for the first four coils.

3.2 Model with microvaristors in the insulation

In order to simulate the effects of microvaristors in the machine insulation, an electrical model of microvaristor filled insulation material is required. For this purpose, resistor elements V_{Ei} and V_{Ti} ,having a nonlinear *E*–γ (field strength-conductivity) characteristic, are implemented in parallel to C_{Ei} and $C_{Ti,}$, respectively. The *E*–γ characteristic is extracted from the *E*–*J* characteristic by dividing current density by the field strength. Advantage of using an *E*–γ characteristic is that the conductivity at low voltage and even at a voltage equal to zero can be considered.

TNA software can only handle integral values like voltages and currents. But conductance of the non-linear elements depends on field strength, i.e. on the distances between wires and between wires and grounded stator. These distances are generally unknown, Therefore, they must be estimated from the capacitances. This has been done by assuming small plate capacitors between the particular capacitances. Equation (1) shows the formulae of the plate capacitor solved to the distance.

$$d = \frac{A \cdot \varepsilon_0 \cdot \varepsilon_r}{C} \quad (1)$$

Where:

- d = distance (m)
- A = surface (m²)
- C = capacitance (F)
- ε_0 = dielectric constant (F/m)
- ε_r = relative permitivity

By assuming the same surface for all of the plate capacitances a distance of the respective capacitance can be estimated. The high permittivity of the ZnO particles increases the capacitance of the insulation. In order to determine the new insulation permittivity, measurements on microvaristor filled insulation varnish probes were performed. These measurements result in a permittivity of $\varepsilon_r \approx 20$. This value is further used for all capacitances. The model with microvaristors filled insulation is shown in **Figure 8**.

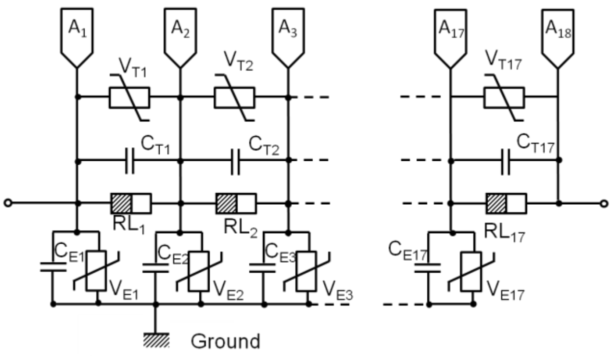

Figure 8: Simulation model with microvaristor filled insulation

4 SIMULATION RESULTS

4.1 Simulation without microvaristors

The simulated voltage distribution is shown in **Figure 7**. The dielectric losses, i.e. the losses between wires and stator, are of main interest. They can be calculated from equation (2).

$$P = \frac{1}{T}\sum_{n=1}^{N} U(t_n) \cdot I(t_n) \quad (2)$$

where:

- U = voltage (V)
- I = current (A)
- P = power (W)
- t_n = time step (s)
- T = cycle time (s)
- N = number of time steps

The transient analysis was performed with a constant time step of 5 ns. Pulse frequency of the inverter was assumed to be 10 kHz. Pulse amplitude and time duration are 560 V and 50 µs, respectively. Rise and fall time of the voltage are identical. **Table 1** shows the results with regard to dielectric losses without microvaristors in the insulation.

Table1: Power losses without microvaristors

Coil	I_{av} in µA	I_{max} in A	P_{av} in µW
1	27.0	1.43	2174
2	19.4	0.64	943
3	10.5	0.46	1656
4	7.9	0.35	1745
5	7.5	0.31	973
6	6.3	0.26	405
7	4.2	0.18	136
8	1.5	0.07	21.9

As shown in **Table 1** the average dielectric losses are very small. Summing up the average dielectric losses at all coils results in a power of 8 mW. The high currents appearing only for a very short time (around 1 µs) are caused by the recharging of the parasitic capacitances and the travelling wave effects.

4.2 Simulation with microvaristors in the insulation

The characteristics shown in **Figure 9** are used for analysing the electric behaviour of the inverter fed drive.

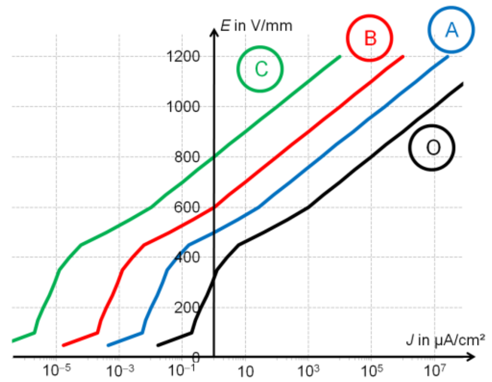

Figure 9: *E–J* characteristics for the simulations.

The three characteristics A, B and C in **Figure 9** are derived from the measured characteristic O by parallel shifts. Characteristic O was established from a microvaristor filled varnish probe with a switching point of 350 V/mm to the measurement could be performed only up to a voltage of approximately 600 V. All values above 600 V were constructed by logarithmic extrapolation. A switching point of 350 V/mm is not high enough for a motor with a dc link voltage of 560 V. The insulation would virtually be short-circuited at this voltage. For this reason the shifted *E–J* characteristics as shown in **Figure 9** are used. In practical implementations such switching points can be achieved by an appropriate manufacturing process of the microvaristors. Characteristics A, B and C have switching points of 500 V/mm, 600 V/mm and 800 V/mm, respectively.

Case 1: Characteristic A

Application of this characteristic will limit the overvoltage to a value of 600 V as it can be seen from **Figure 10**. However, due to the high residual conductance of the microvaristor filled insulation at nominal voltage the dielectric losses, which are shown in **Table 2**, are extremely high. The overall losses (sum of all coils) are about 290 W. Furthermore, it can be observed that the high current occurs only at the first coil, compared to the others. Also, voltage steepness of coils 2 to 8 becomes lower due to the higher capacitance of the microvaristor filled material, requiring a longer time to be charged.

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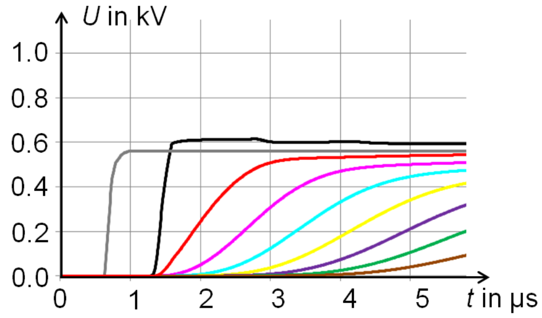

Figure 10: Voltage distribution in the motor when applying characteristic A

Table 2: Dielectric losses with *E–J* characteristic A

Coil	I_{av} in mA	I_{max} in A	P_{av} in W
1	138.4	6.58	261.9
2	13.95	0.99	22.7
3	3.79	0.73	4.13
4	0.87	0.58	0.88
5	0.03	0.49	0.14
6	0.10	0.41	10.5 m
7	0.07	0.31	245.4 µ
8	0.02	0.13	30.00 µ

Average losses of nearly 290 W, as it can be seen in **Table 2,** are not acceptable, because this would destroy the motor insulation.

Case 2: Characteristic B

Introducing microvaristors with characteristic B of Figure 9 results in a decrease of the losses (see **Table 3)**.

Table 3: Dielectric losses with *E–J* characteristic B

Coil	I_{av} in mA	I_{max} in A	P_{av} in W
1	77.22	5.95	52.7
2	4.67	1.04	2.8
3	1.17	0.77	0.73
4	0.249	0.62	0.21
5	52.35 µ	0.52	43 m
6	104.40 µ	0.44	34.5 m
7	73.40 µ	0.32	18 m
8	27.49 µ	0.13	28.5 µ

Comparison of the results of these two characteristics show that the dielectric losses in case 2 are, with nearly 60 W, very high, but much lower than case 1. Both cases show high losses in the first coil as well as same high conductivity of the microvaristor filled insulation at nominal voltage. As it can be seen from **Figure 11**, the voltage is limited to 700 V, which is higher than in the previous case but still a notable effect in overvoltage reduction.

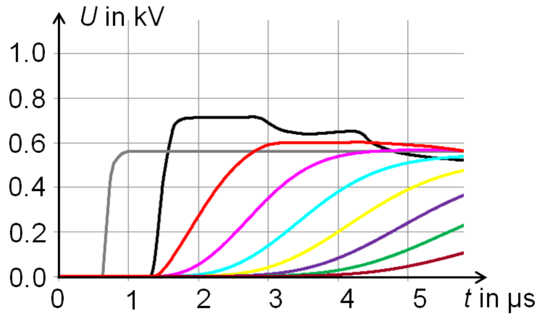

Figure 11: Voltage distribution in the motor when applying characteristic B

Case 3: Characteristic C

Using microvaristors of characteristic C in Figure 9 (switching point 800 V/mm) results in further decreased dielectric losses, as can be seen in **Table 4.**

Table 4: Dielectric losses with *E–J* characteristic C

Coil	I_{av} in µA	I_{max} in A	P_{av} in mW
1	10459	4.28	8987
2	656	1.29	565
3	122	0.96	17.2
4	147	0.75	2.5
5	138	0.61	0.8
6	112	0.50	0.4
7	74	0.37	0.16
8	28	0.15	0.03

The overall average dielectric losses are now less than 10 W. These values are acceptable to operate the motor. Considering the voltage distribution (**Figure 12**) it can be observed that an overvoltage level of 900 V is achieved, which is a reduction of 10 % compared to the case without overvoltage protection (Figure 7).

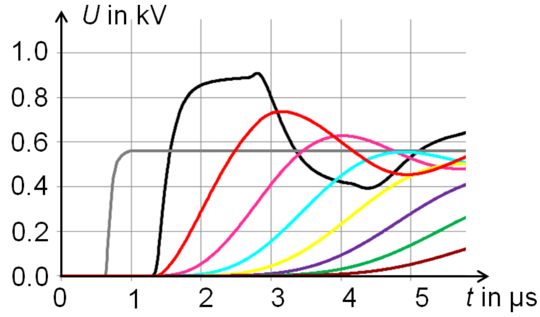

Figure 12: Voltage distribution when applying characteristic C

5 CONCLUSION

In this contribution the possible effects of microvaristors in the insulation of inverter fed drives are investigated. In order to perform simulations, some simplifications have to be introduced. But when assuming plate capacitors as a replacement of the cpacitances between the wires and between wires and ground allows to estimate the electric behaviour of microvaristor filled insulation. Simulations give the following results:

- Overvoltages due to travelling wave effects can be limited.
- Lower switching points result in a better voltage distribution within the machine.
- But low switching points may cause unacceptably high dielectric losses.
- Increasing the switching point reduces losses, but also reduces the limitation of overvoltages. A compromise between low losses and low overvoltages has to be found.
- A simulation tool for this purpose is now available.

In future research, after having found an optimal dimensioning of the microvaristor characteristic, long term behaviour of microvaristor filled insulation systems in inverter fed electrical machines has to be investigated.

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