MODELLING EPOXY-MICA MOTOR INSULATION FOR ARCING EARTH FAULT STUDIES

J. M. Van Coller[1*] and P. Warner[2]
[1]School of Electrical and Information Engineering, University of the Witwatersrand,
1 Jan Smuts Avenue, Johannesburg, South Africa
[2]Anglo American Technical Division, 45 Main Street, Marshalltown, Johannesburg,
South Africa
*Email: j.vancoller@ee.wits.ac.za

Abstract: Unearthed networks can experience arcing earth faults when the earth fault current is insufficient to establish a permanent conducting path to earth, with the result that the earth fault current gets interrupted at the first current zero. This causes the network capacitance to be charged up to a large voltage, which, when sustained, can cause a repeat earth fault at the same location. A sequence of these events can cause voltage escalation with a risk of another earth fault developing elsewhere on a different phase. Involvement of different phases causes the single earth fault to become a phase-phase fault with considerably higher fault currents that can lead to extensive damage to equipment. Of particular interest in this study was the network consisting of a large gearless mill drive (GMD) motor fed off a cycloconverter. The epoxy-mica insulation used in MV motors has a relatively high tan δ at power frequencies (50 Hz) compared with polymeric cables. An investigation was initiated to determine whether the dielectric losses of the epoxy-mica insulation of MV motors could provide sufficient damping to prevent the above voltage escalation. The conclusion was that the high frequency damping contributed by the epoxy-mica insulation can be ignored in arcing earth fault studies.

1 INTRODUCTION

Large mills are used to process the considerable quantities of ore produced by (for example) copper and platinum mines. These mills are often of the gearless mill drive (GMD) type where a ring motor is controlled via a cycloconverter. The network consisting of the cycloconverter connection to the ring motor is usually unearthed to minimize damage to the motor if an internal earth fault occurs. These motors are difficult to protect completely from moisture ingress and hence the risk of an internal earth fault is high. The economic consequences of extended repair work, in terms of lost production, can greatly exceed the cost of the motor itself.

Unearthed networks can experience arcing earth faults, where the earth fault current is too small to establish a permanent conducting path to earth and the fault current gets interrupted at the first current zero. This half-cycle of earth fault current causes the motor capacitance-to-earth to be charged to a high value since the earth fault current gets interrupted at the voltage peak of the resonant half-cycle. This raised voltage-to-earth, if sustained, can cause a repeat earth fault at the same location. A sequence of these earth fault events can cause voltage-to-earth escalation with a risk of another earth fault elsewhere.

A double earth fault involving different phases forms a phase-phase fault with considerably higher fault currents (largely contributed by the motor) that can do considerable damage to equipment.

The epoxy-mica insulation used in MV motors (including in gearless mill drives) has a relatively high tan δ at power frequencies (50 Hz). An investigation was initiated to determine whether the epoxy-mica insulation of MV motors could provide sufficient damping to prevent the above voltage-to-earth escalation.

2 ARCING EARTH FAULT PHENOMENON

An arcing earth fault occurs when the earth fault current is too small to establish a permanent conducting path to earth and the earth fault current gets interrupted at the first current zero - Figure 1.

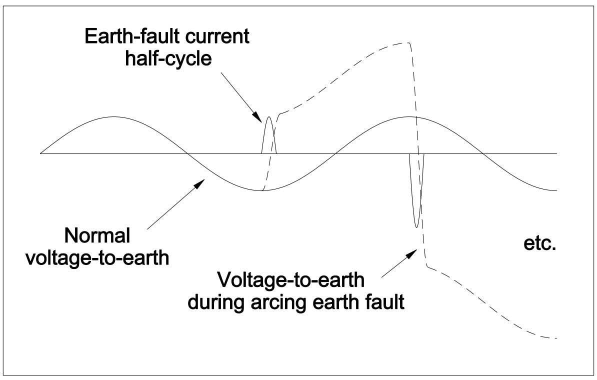

Figure 1: Waveforms for an arcing earth fault [1]

The raised voltage-to-earth applies additional stress to the insulation between the conductors and earth (slot insulation). The likelihood of the original earth fault being re-established is therefore high and in Figure 1 this is assumed to occur when the raised voltage-to-earth reaches its new peak value. Because of the greater voltage-to-earth when the earth fault is re-established, the voltage-to-earth overshoots to a higher negative value as shown in Figure 1. With successive earth faults the voltage-to-earth escalates until a permanent conducting path to earth is established.

The greatest threat with the arcing earth fault is that another earth fault occurs on a different phase. This causes the single earth fault to evolve into a considerably more serious phase-phase fault with serious consequences to the motor.

In Figure 1 no damping is assumed such that during the transient, the voltage overshoot (past zero volts) is equal to the voltage-to-earth immediately prior to the earth fault. This maximizes the voltage escalation.

In practice, damping is present and a possible contributor to the damping is the dielectric loss of the MV motor insulation itself.

3 ASSUMED MODEL OF THE EPOXY-MICA MV MOTOR INSULATION

The assumed model of the epoxy-mica MV motor insulation to earth is shown in Figure 2

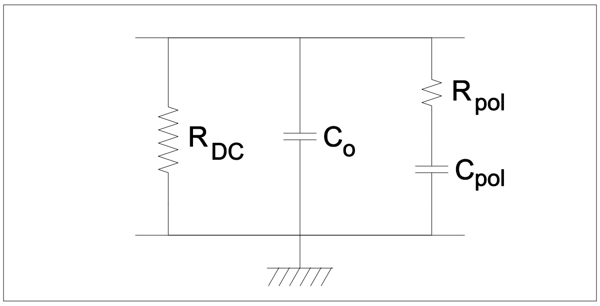

Figure 2: Assumed model of the epoxy-mica motor insulation-to-earth

The resistance R_{DC} represents the leakage current of the epoxy-mica insulation. Typically this resistance has a very high value when the insulation is healthy (>10 GΩ for the entire motor)(this resistance value is usually continuously monitored to detect insulation problems) and hence can be ignored in the model used for simulating arcing earth faults. This implies that the raised voltage after the earth fault transient has no discharge path and can be assumed to remain until the next earth fault event (as shown in Figure 1).

The capacitance C_o represents the geometric capacitance to earth of the motor insulation (if the epoxy-mica insulation were replaced with a vacuum). This capacitance, by definition, cannot contribute any losses and hence does not have a series resistor.

For a relative permittivity of the epoxy-mica insulation of ε_r, and for a total motor insulation-to-earth capacitance of C_{motor},, the value of C_o can be calculated using Equation (1)

$$C_o = \frac{C_{motor}}{\varepsilon_r} \qquad (1)$$

The balance of the total motor insulation-to-earth capacitance is then assigned to C_{pol} as shown in Equation (2).

$$C_{pol} = C_{motor} - \frac{C_{motor}}{\varepsilon_r} = \frac{\varepsilon_r - 1}{\varepsilon_r} C_{motor} \qquad (2)$$

For a total motor insulation-to-earth capacitance of 6,8 μF and a relative permittivity of the epoxy-mica insulation of 4 [2] this gave values of 1,7 μF for C_o and 5,1 μF for C_{pol}.

The resistance R_{pol}, represents the dielectric losses in the epoxy-mica insulation. These losses are associated with the polarization processes within the insulation and must be determined at the frequency of oscillation of the earth fault current. This resistance will then determine the level of overshoot and also the level of voltage escalation when there is an arcing earth fault.

The only information readily available concerning the dielectric losses is that provided by the tan δ value determined at the power frequency (50Hz). This value is typically 0,03 (or 3%) for epoxy-mica insulation. This relatively high value was the reason for the hypothesis that the epoxy-mica insulation may be able to provide significant damping during arcing earth faults.

Measurements at the power frequency (50 Hz) are not directly applicable at the resonant frequencies associated with arcing earth faults as the polarization processes in solid insulation have long time constants such that the polarization is considerably reduced at higher frequencies. This leads also to lower dielectric losses at higher frequencies.

Since the frequencies of interest are in the MHz range, a method for measuring the dielectric losses at this frequency was devised and is discussed in Section 4.

4 MEASUREMENT OF THE DIELECTRIC LOSS AT HIGH FREQUENCIES

4.1 Introduction

A simple method for measuring the dielectric loss of any capacitor is to discharge the initially charged capacitor through an inductor. From the measured waveforms the damping and hence loss can be determined.

The problem arises when the inductor itself has significant losses at the measurement frequency.

An improved method involves comparing the waveforms measured with the motor insulation-to-earth capacitance discharging through an inductor with the waveforms of a low-loss capacitor discharging through the same inductor where the frequencies are identical (implies that the low-loss capacitor must have the same capacitance as the sample of motor insulation tested (in this case a single motor stator bar)).

4.2 Test circuit

The single motor stator bar was tested out of its slot so it was necessary to wrap the stator bar with aluminium foil along its full length.

Since the stator bar was from a motor with a voltage rating of approximately 4 kV, the epoxy-mica insulation-to-earth included an outer semiconductive layer (corona shield). This ensured consistent contact with the epoxy-mica insulation over its full length.

For the high frequency measurements, the air-cored inductors were wound using Litz wire to reduce the inductor losses.

A schematic of the test circuit is shown in Figure 3.

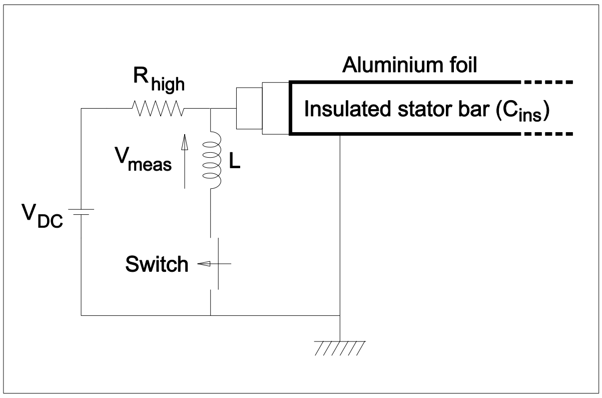

Figure 3: Laboratory circuit used to measure the high frequency losses of motor stator bar insulation

A photograph of the test set-up is shown in Figure 4.

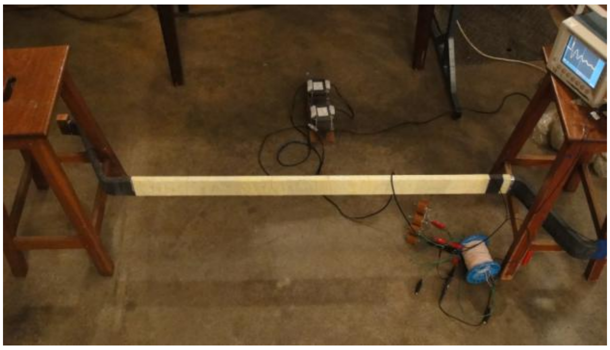

Figure 4: Photograph of the test set-up

4.3 Typical measured waveforms

Typical measured waveforms are shown below for when the motor stator bar was replaced with a low-loss capacitor (with the same capacitance value) - Figure 5 - and when the stator bar itself was tested - Figure 6.

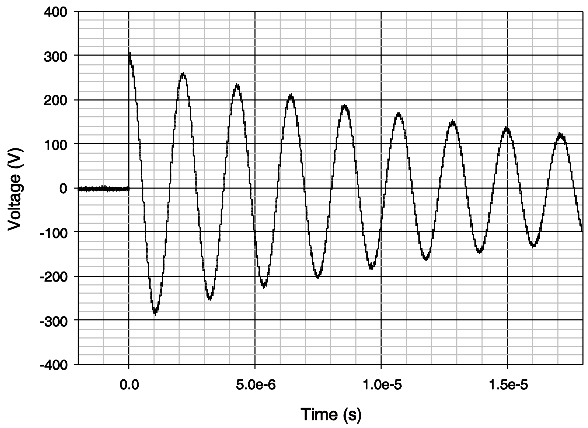

Figure 5: Discharge voltage waveform when a low-loss capacitor was discharged through the inductor

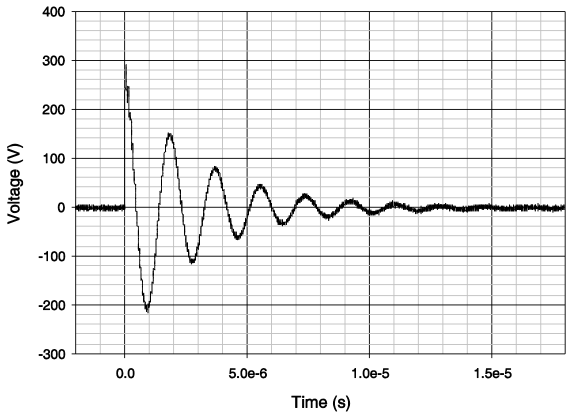

Figure 6: Discharge voltage waveform when the stator bar capacitance-to-earth was discharged through the same inductor

The testing was repeated at various frequencies and the results are presented in Table 1.

Table 1: Measured values for R_L and R_{pol}

Frequency (Hz)	R_L (Ω)	R_{pol} (Ω)
1 MHz	1,6 Ω	6,3 Ω
500 kHz	1,9 Ω	15 Ω
350 kHz	2,7 Ω	20 Ω
70 kHz	52 Ω	50 Ω
550 Hz	21 kΩ	3 kΩ

The values of R_L were obtained by determining the values of R in the series RLC discharge circuit that reproduced the measured damped voltage waveforms for the case when a low-loss capacitor replaced the stator bar.

The higher values of R_L recorded at the lower frequencies were because at these lower frequencies the inductor used was constructed using single strand wire on an air core (70 kHz) and single strand wire on a laminated iron core (550 Hz). These inductors are expected to have higher losses at the respective measurement frequencies.

The values of R_{pol} were obtained by assuming the previous values of R_L for the inductor and then determining the values of R_{pol} in the equivalent circuit of Figure 2 that reproduced the measured damped voltage waveforms for the case when the stator bar insulation was tested.

The value of R_{pol} used in the simulations of the arcing earth faults was the value calculated at 1 MHz.

The values determined from the above laboratory experiment applied only to a single motor stator bar and needed to be extrapolated to the entire motor. For the simulations, the total motor capacitance was as specified for the motor (6,8 μF), and the polarization resistance determined for the single stator bar was divided by the number of stator bars.

5 SIMULATION WAVEFORMS

The cycloconverter was modelled using ATP and the motor was modelled by splitting each stator phase winding into ten segments. The segments were modelled as pi-sections with series coupled inductances and with capacitances-to-earth obtained from the total motor capacitance-to-earth shared between all pi-sections.

The dielectric losses were modelled as shown in Figure 2.

For the waveforms in Figure 7, an arcing earth fault was simulated by closing a switch when the voltage across the switch was a maximum and opening the switch at the first current zero. Figure 7 also shows the voltage-to-earth escalation with successive arcing earth faults.

The high voltages-to-earth reached during the arcing earth fault relative to the normal voltages-to-earth prior to the first earth fault should be noted.

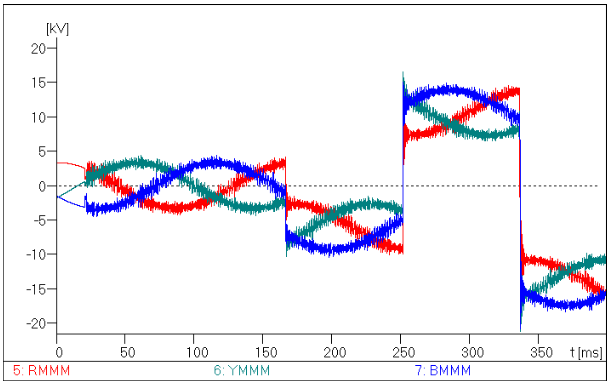

Figure 7: Motor terminal voltage-to-earth waveforms (including cycloconverter switching) with three consecutive arcing earth fault events on the red phase

6 CONCLUSION

The aim of the investigation was to determine whether the epoxy-mica insulation used in MV motors can contribute any meaningful damping to arcing earth fault waveforms.

The conclusion was that due to the limited polarization occurring at the high frequencies associated with the arcing earth fault resonances, the damping contributed by the epoxy-mica insulation is negligible.

7 ACKNOWLEDGMENTS

Both authors would like to acknowledge Anglo Technical Services for funding the simulations, the laboratory testing and arranging the stator bars for the tests

The first author would like to also acknowledge funding of the University Electric Power Research Programme by Eskom via the Tertiary Education Support Program (TESP).

8 REFERENCES

[1] J.F. Peters, J. Slepian: "Voltages induced by arcing grounds", AIEEI, Vol. 42, pp. 478- 493, 1923

[2] G.C. Stone, E.A. Boulter, I. Culbert, H. Dhirani, "Electrical Insulation for Rotating Machines - Design, evaluation, ageing, testing and repair" (book), IEEE Press, 2004