Electrical Stress and Parasitic Currents in Machine Elements of Drivetrains with Voltage Source Inverters

Alexander Furtmann and Gerhard Poll

Introduction

Modern drivetrains with voltage-source inverters not only offer advantages like, for example, variable speed operation, increased efficiency and higher dynamics — but also an increase in failures caused by induced parasitic currents. One of these currents, the so called EDM current, is known for damaging bearing raceways and lubricant, thus leading to a reduced lifetime. EDM currents occur if the voltage across a lubricant film is too high and the maximum dielectric strength in the contact is exceeded. The source of the voltage is what is known as "common-mode" voltage, which is inherent in voltage source inverters with two discrete switching states. While the behavior of electric motors has been vigorously investigated in recent years (Refs. 2–6), the effects of parasitic currents on the whole drivetrain have yet to be a focus of research. Damage on tooth flanks and gearbox bearings due to parasitic currents are also known.

Regarding EDM currents, the electrical capacitances of a system are its most important parameter. In a drivetrain, all machine elements with a separating lubricant film — e.g., rolling element bearings, journal bearings and gears — behave like an electrical capacitor whose capacitance depends on contact conditions like film-thickness and contact area, but also on the lubricant that acts as the dielectric. Further attention is required for the gear mesh, as a lot of the contact parameters vary over the path of contact (Ref. 1).

Basics

Electrical stress due to inverter-induced, parasitic currents can be traced back to two root effects, according to Mütze (Ref. 3). These effects are high-frequency ground currents generated by the fast switching of the inverter and the so called common-mode voltage, with the latter being responsible for EDM currents. Due to the fact that voltage-source converters only have discrete switching states, the sum of the three output voltages, in contrast to a sinusoidal supply, is not equal to zero. As a result, a voltage that is proportional to the common-mode voltage occurs at the motor bearings as the parasitic capacitances in the system form a capacitance voltage divider. If the voltage over the lubricant film exceeds the dielectric strength of the lubricant, a breakdown and thus an EDM current (electric discharge machining) occurs. Due to the high energy in such a discharge, the lubricant may be negatively affected and the metal surfaces can melt. Very high, energetic discharges can also vaporize parts of the surface, which was shown to be very harmful in regards to creating fluting in bearings (Ref. 7). For a better understanding and a prediction of EDM currents, it is important to know the amplitude of the voltage at the different machine elements. To calculate the voltages in an electric motor, equivalent circuits based on capacitors were developed (for example, by Hausberg or Mütze). These networks consist of the capacitance between rotor and frame C_{rf}, winding and frame C_{wf}, winding and rotor C_{wr} and the bearing capacitances C_b. Recent research expanded this network to the gearbox behavior. Using the example of a single-staged gearbox, Figure 1 gives the combined equivalent circuit of motor and gearbox combination. For the gearbox, the tooth capacitance over the gear mesh C_t was introduced. This capacitance is not constant for one operation point, as it is changing due to the movement of the teeth (Refs. 1, 8-9).

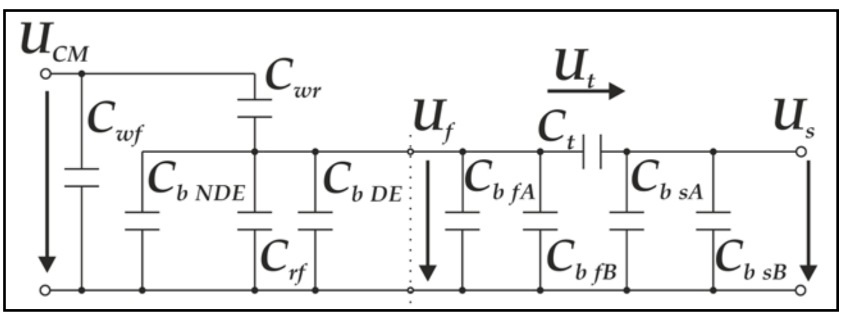

Figure 1 Combined equivalent circuit for a drivetrain consisting of a motor and a single-stage gearbox (fast-shaft with index f, slow shaft with index s).

As shown (Ref. 8), the voltage divider of the common-mode voltage U_{CM} to the voltage U_f at the fast-shaft, and the one to the voltage Us at the slow-shaft, can be determined with Equations 1 and 2:

$$BVR^{+} = \frac{U_f}{U_{CM}} = \frac{C_{wr}}{C_{wr} + C_{rf} + C_{bDE} + C_{bNDE} + C_{bfA} + C_{bfB} + \frac{C_t \cdot (C_{bsA} + C_{bsB})}{C_t + C_{bsA} + C_{bsB}}} \quad (1)$$

$$BVR_{Drivetrain} = \frac{U_f}{U_{CM}} = GVR \cdot BVR^{+} = \frac{C_t}{C_{bsA} + C_{bsB} + C_t} \cdot BVR^{+} \quad (2)$$

This paper was first presented at the International VDI Conference on Gears 2017, Garching/Munich [VDI-Berichte 2294, 2017, VDI Verlag GmbH] and is reprinted here with VDI approval.

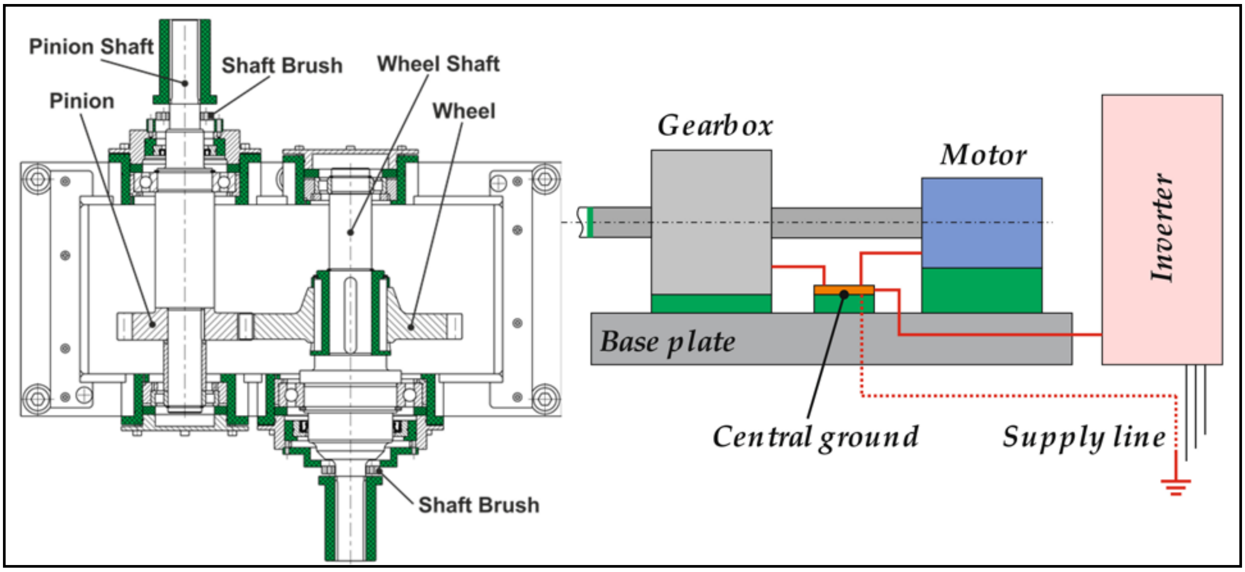

Figure 2 Gearbox with insulations (left) and grounding concept of the drivetrain (right).

Experimental set-up. To measure the currents and voltages in the drivetrain, a special test rig was designed and built. The system was designed as an electrical back-to-back test rig to with a frequency-controlled motor and generator on the slow and fast side of a single-staged gearbox. In an unprepared system, it is not possible to determine the current paths exactly due to the large contact areas of the different machine elements. A way around this problem was found by insulating the elements from each other and then setting up defined bridges for the insulation. Through these bridges the whole current of a component has to flow, and thus it is an easy spot for measurements. While the insulation of the gearbox and motor housings from the frame can be achieved quite easily with large plastic plates, the insulation of single machine elements requires more effort. For the drive unit a motor with insulated bearing shields was used. This motor was already used in the research by Hausberg (Ref. 2). The driven machine was insulated from the gearbox by the use of an insulated coupling. For the gearbox a modified gearbox as shown in (Ref. 1) was used. Figure 2 (left) shows the gearbox with insulations between the bearings and the housing. As the current over the gear mesh is not directly measurable due to the non-stationary parts, it can only be observed by measuring all other currents and then deriving the gear mesh currents. In Figure 2 (right) and Figure 3, all the necessary measuring points and the defined ground system are depicted.

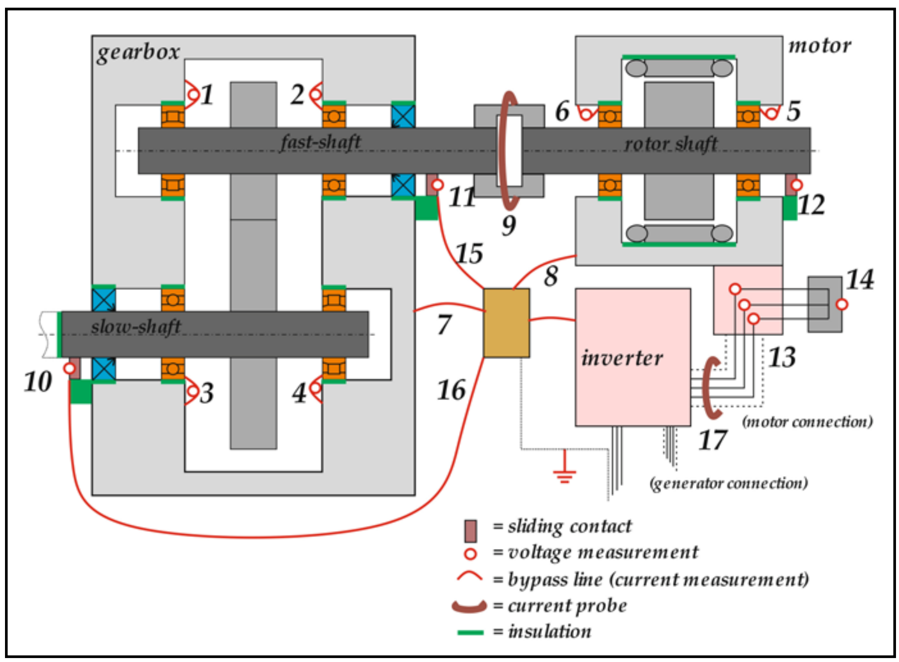

Figure 3 Drivetrain with multiple measuring points.

Due to the high-frequency nature of the parasitic currents, it was necessary to use probes and scopes that are suited for such frequencies. For the measurements two 4-chanel oscilloscopes Tektronix MDO4054C with a bandwidth of 500 MHz and a sampling rate of 2.5 GS/s were used in a master-slave-arrangement (Fig. 4, left) to enable simultaneous triggering at specific conditions like a breakdown in a defined bearing. The bearing currents were measured with current probes Pearson Model 6595 (Fig. 4, right) and the voltages with differential voltage probes Tektronix TMDP0200. To avoid needing three voltage channels for the common-mode voltage, an artificial neutral point by Yokogawa was used.

Results

First measurements were done to evaluate the predicted behavior of the gearbox as a voltage divider. Therefore the common-mode-voltage U_{CM}, the shaft voltages U_f and U_s, and the voltage over the gear mesh were measured. Figures 5 and 6 show the behavior of the voltages for two different operation points. Figure 5 is a very good example for the voltage dividing behavior, as all voltages follow the common-mode voltage with a reduced amplitude. The amplitude of the voltage is also further reduced along the gearbox, as was predicted by the model. Furthermore it can be seen that the voltage of the slow shaft and the voltage over the gear mesh match the voltage of the fast shaft. Contrary to this behavior, Figure 6 shows something else — over the measurement almost no voltage is built up at the slow shaft, while the fast shaft voltage and the gear mesh voltage are the same. This shows that at these conditions the slow shaft bearings have no separating lubricant film and thus behave like a direct ground connection. As a result the gear mesh and the fast shaft bear-

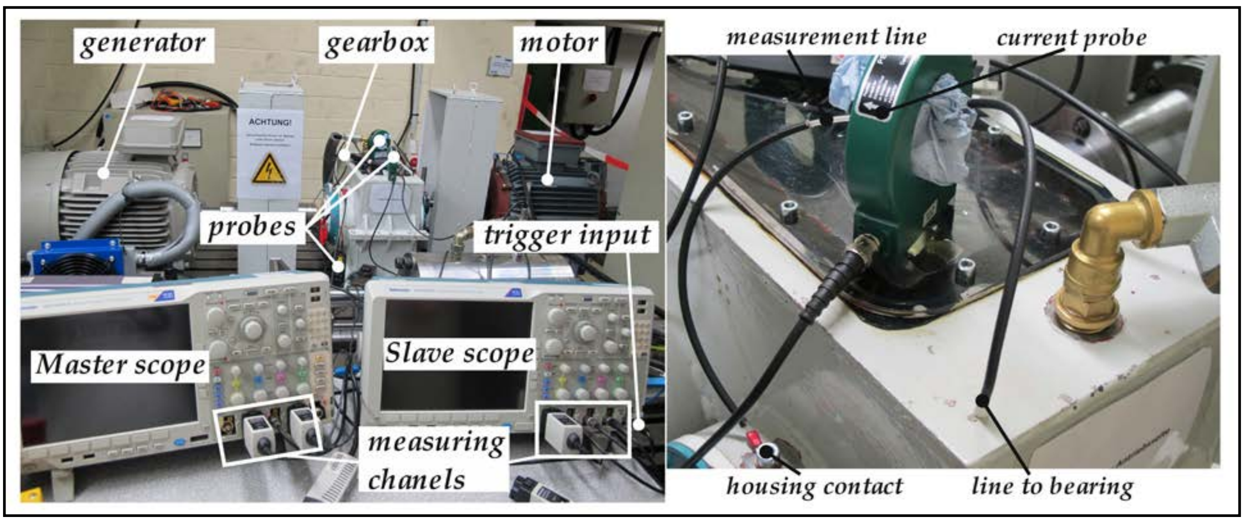

Figure 4 Measurement setup with two oscilloscopes in a master-slave arrangement (left) and current probe for measuring bearing currents (right).

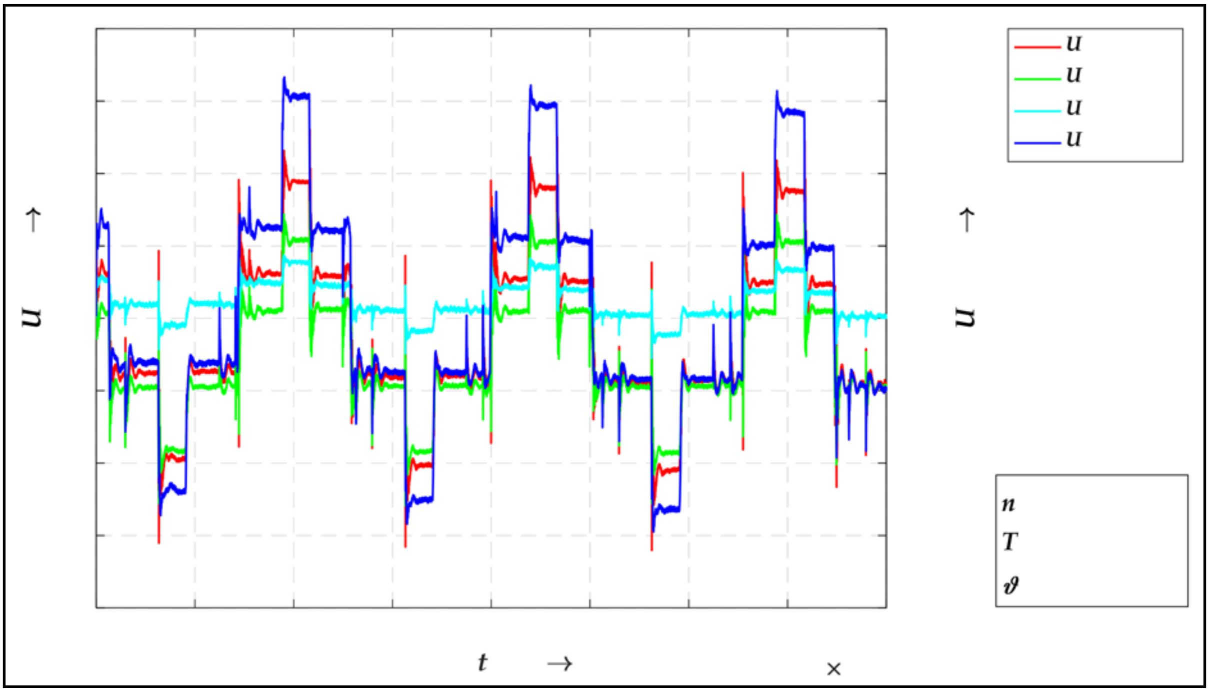

Figure 5 Measured voltages in the drivetrain with a clearly visible voltage divider.

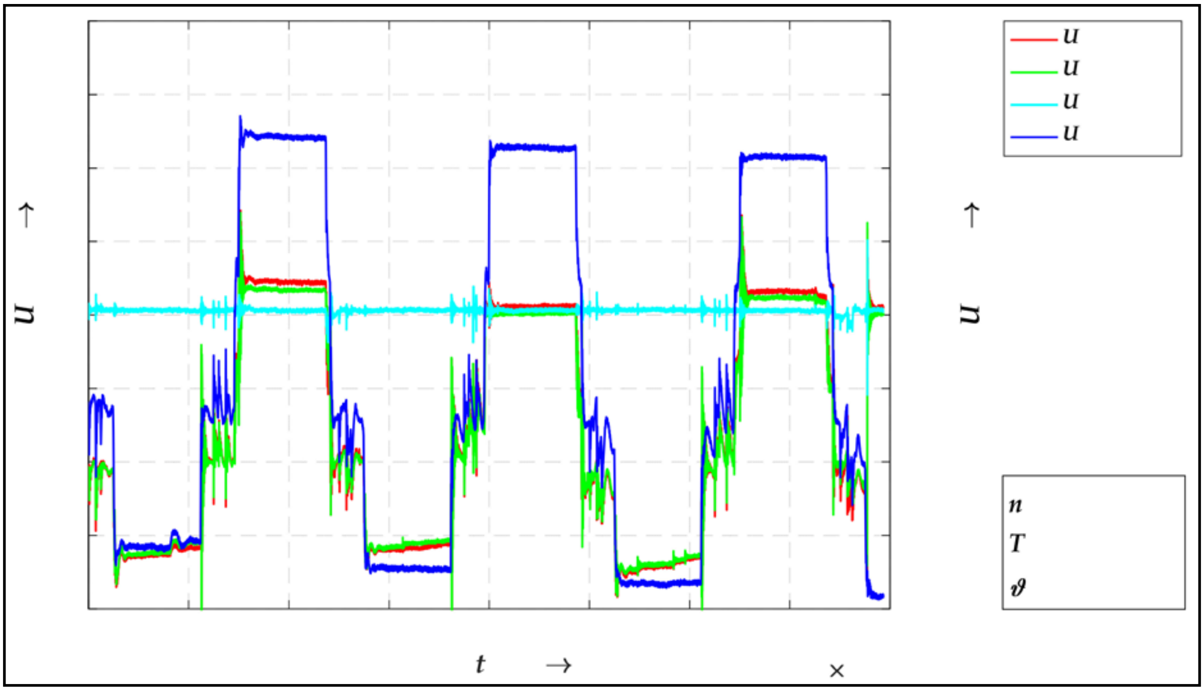

Figure 6 Measured voltages in the drivetrain with no voltage at the slow-shaft due to mixed lubrication.

Table 1 Comparison of measured and calculated voltage divider			
	measurement	simulation $C_{t,min}$	simulation $C_{t,max}$
BVR^{+}	3.164%	2.76%	2.8%
GVR	29.7%	36.7%	27.9%
$BVR_{Drivetrain}$	0.94%	1.01%	0.78%

ings are in a direct loop and therefore must have the same voltage. The measurements also confirm the non-constant behavior of the gear mesh capacitance. While the common-mode voltage remains constant in one step, the voltage in the loop of fast shaft and gear mesh is varying and thus the capacitance of this loop also has to be changing.

To compare the voltage dividing behavior, a simulation of the drive train with calculated capacitances (Refs. 1, 8-9) is done based on a measurement of the common-mode voltage. In this simulation the breakdown voltage is set to large values so that there is no negative influence of discharge events on the curve shape. This was not possible for the measurements, however, so it was necessary to analyze parts of the signal where the voltage levels were not shifted due to a previous breakdown. Figure 7 shows the results of the simulation with the gear mesh capacitance assumed constant at the minimum calculated value. An evaluation of the different voltages and the resulting voltage dividers for the simulation and measurement are found in Table 1. While the *BVR+* is a little underestimated in the calculations, the *GVR* and

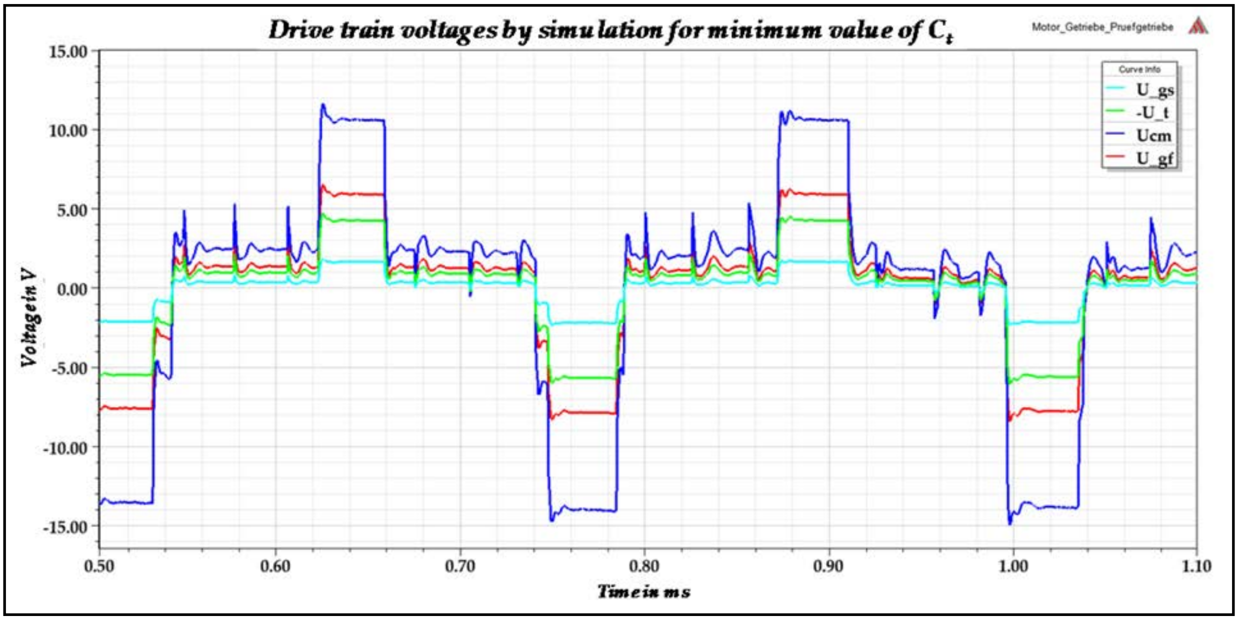

Figure 7 Calculated voltages using the simulation model and a measured common-mode voltage.

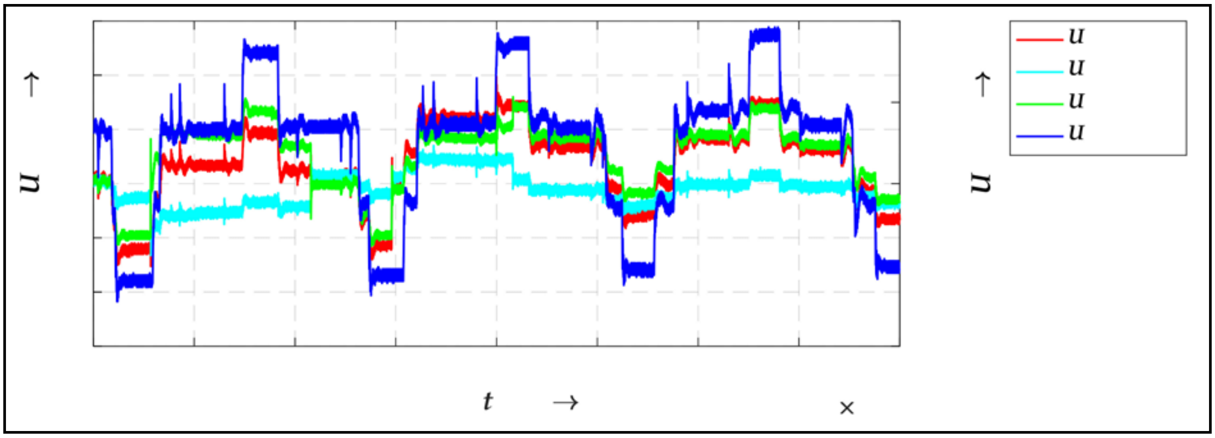

Figure 8 Measured voltages in the drivetrain with insulated motor bearings.

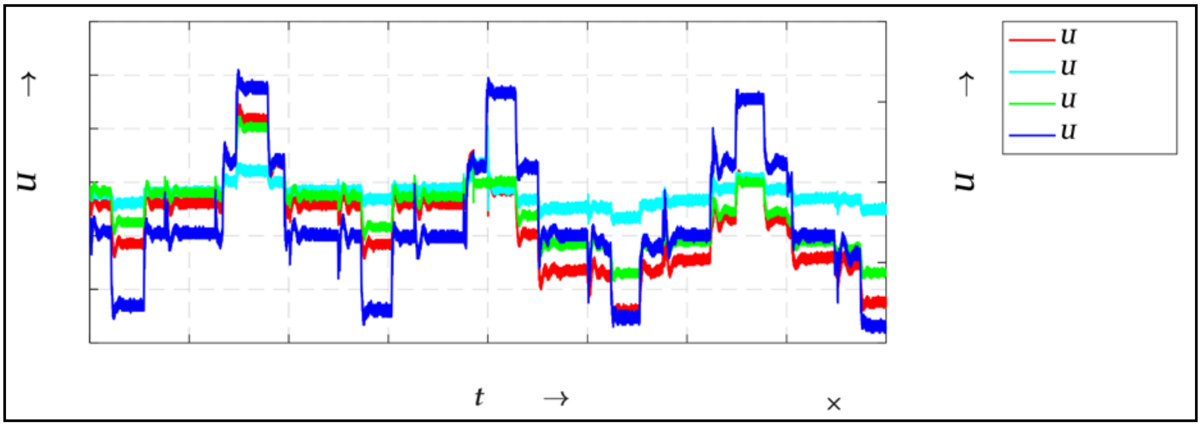

Figure 9 Measured voltages in the drivetrain in train with insulated motor and fast-shaft bearings.

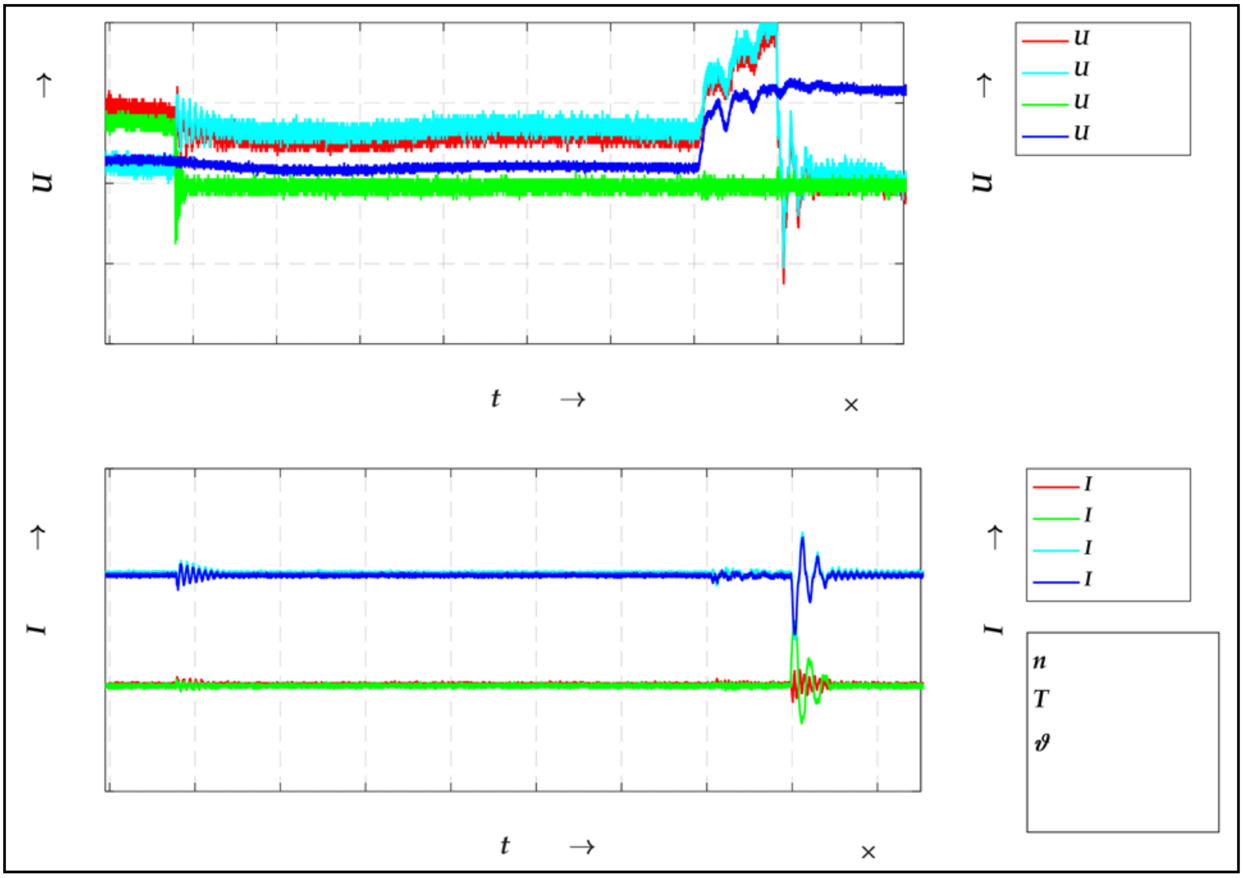

Figure 10 Breakdown of the gear mesh voltage and subsequently in the slow-shaft bearings.

Table 2	Voltages for different systems with and without insulations				
	normal system	hybrid bearings in motor	insulated fast-shaft and motor bearings	insulation + conductive slow-shaft bearing	insulation + conductiye gear mesh
U_{gf}	9.1V	12.4V	14.9V	13.1V	13.7V
U_t	4V	5.4V	6.5V	13.1V	OV
U_s	5.1V	7V	8.4V	OV	13.7V

BVR- $_{Drivetrain}$ show a good correlation as the measured values are in between the two calculated extreme values for the minimum and maximum of the gear mesh capacitance *Ct*.

Influence of Insulations on Drivetrain Behavior

Insulations appear to be one possible solution to avoid harmful parasitic currents. Especially for motor bearings, the usage of insulated bearings or hybrid bearings is quite normal. For this research the influence of such insulations on the remaining part of the drivetrain was investigated. Figure 8 shows the voltages in the test rig with insulated motor bearings. The curves show that voltages exist at the gearbox shafts. The voltage drops during fix steps of the common-mode voltages also show that there still are breakdown events in the gearbox. An analysis of the voltage divider leads to a BVR^+ of 3.4% and a $BVR_{Drivetrain}$ of 0.73%.

In a next step also the fast-shaft gearbox bearings were insulated by removing the shorting wire that was used to measure the bearing current over these bearings. Figure 9 shows the results of these measurements that at a first glance look quite similar. However, the BVR^+ increased to 3.8% and the $BVR_{Drivetrain}$ increased to 0.88% of the common-mode voltage. This increased voltage divider leads to EDM-currents at the slow-shaft of the gearbox (Fig. 10). In the figure one can see at first a breakdown over the gear mesh with small, capacitive currents as the systems capacitors are reloaded. As a result, the slow-shaft voltage *Us* increases to the same level as the fast-shaft voltage $U_f$because they are in the same loop now. With the next voltage step of the common-mode voltage, the voltage exceeds the critical level for the bearing GL4 and a discharge occurs. This discharge is also fed by the other capacitances of the network, as is shown due to the almost identical currents that flow through the fast-shaft, the bearing GL4 and the ground connector.

This behavior shows that it is important to apply insulation as a mitigation for EDM currents carefully. A wrong usage might just shift the electrical stress to other parts of the drivetrain and might even increase it as well. In Table 2, this is further demonstrated for an example system. With each insulation — starting with the motor bearings — the shaft voltages increase. The last two columns show the effect if one of the remaining contacts becomes conductive, due, for example to a discharge or just mixed lubrication from the operation conditions — and how this affects the remaining voltages. The elements on the slower side of the gearbox might face large voltages that they probably cannot endure as their film-thickness and thus their critical breakdown voltage is comparatively low due to the low hydrodynamic speed. As the torsion makes it difficult to insulate the gears, they are especially in danger if all other components are insulated. The dynamic of the gear mesh will probably lead to discharges and thus damage the tooth flanks.

Conclusion

This work gives a small impression on the effect and the behaviour of electric stress in drive trains with gearboxes. As an electric system, the gearbox behaves like a capacitance voltage divider due to the separating lubricant films in the machine elements. Insulations like hybrid bearings might reduce the electrical stress in one component like a motor, but it is important to consider the whole drive train as otherwise the problems just might be moved to other parts. As an insulation of the pinion or the wheel is quite difficult and the lubricant film in the gear mesh is not so stable due to the dynamic of the system, these components are especially endangered in regards of harmful discharges. Depending on the system this could lead to even higher costs if for example a gearbox with long delivery time has to be repaired or replaced compared to standard motor. **PTE**

Acknowledgment. *The authors wish to thank the Siemens AG for partially funding and supporting this project.*

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