High-current Capability of Coaxial Cables in Magnetoforming Applications*

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Abstract

Magnetoforming technology often requires impulse current amplitudes of several hundred kiloamps, at pulse durations between 30 µs and >100 µs. Often, it is required to provide the impulse via a flexible transmission line (cable) in order to allow the forming coil to be positioned correctly. These cables have to withstand the high pulse currents without deterioration for a large number of pulses. In addition, it is necessary to minimise the inductance of the cable connection, as an increase in inductance negatively influences the efficiency of the installation as a whole, whence low-inductance coaxial cables are required which are able to fulfil all of these requirements simultaneously.

Manufacturers normally do not specify the impulse current capability of coaxial cables, as this is not necessary for most standard applications. Therefore, experiments were performed to explore the limits of commercial medium high voltage cables in regard of their impulse current withstand capability for these specific impulse parameters.

A coaxial medium voltage cable has been tested at single pulses of ca. 100 µs duration, at amplitudes between 30 and 140 kA. The radial deformation (expansion) of the cable was detected with a high-resolution, high-speed camera. At a frame rate of 9000 frames/s the expansion of the cable has been determined as a function of the current amplitude. We observed dynamic changes of the cable diameter at currents above 81 kA, reaching up to 1.26 mm increase in diameter at 142 kA pulse amplitude. Above 100 kA, part of the deformation becomes irreversible, with cumulated permanent changes of up to 1 mm. The measurements are used to estimate the operating range of these cables.

Keywords

Magnetic forming; impulse current; coaxial cable; operating range

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* *This work has been funded by the Sächsische AufbauBank SAB, Saxonia, Germany within the scope of the project "Grundlagen zur elektromagnetischen Formgebung flächiger Karosseriebauteile", project number 8942/144,9 as part of a collaboration with the Fraunhofer Gesellschaft (FhG) Chemnitz, Germany; the authors thank T. Koch from the FhG Chemnitz for his support of this work.*

1 Introduction

Magnetoforming technology often requires impulse current amplitudes of several hundred kiloamps, at pulse durations which are typically between 30µs and >100 µs. In practical applications, it is often required to provide the impulse via a low-impedance, flexible transmission line (cable) in order to allow the forming coil to be positioned according to the forming process / work piece requirements. These cables have to withstand the high pulse currents without deterioration for a large number of pulses, which in some applications can reach millions. Additionally, it is necessary to minimise the inductance of the cable connection, as an increase in inductance negatively influences the efficiency of the installation as a whole, whence low-inductance coaxial cables are required; these cables have to fulfil all of these requirements simultaneously.

Manufacturers normally do not specify the impulse current capability of coaxial cables, as this is not necessary for most standard applications. Therefore, experiments have been performed to explore the operating range and limits of commercial medium high voltage cables in regard of their impulse current withstand capability for these specific impulse parameters.

In particular, the measurements described hereafter have been made to determine the radial deformation (blow-up) of the cable, i.e. the outer conductor of the coaxial cable, which is pushed outward by the magnetic field inside the cable during a high-current pulse. Distinction has been made between dynamical (reversible) deformation, and irreversible deformation, i.e. a permanent increase in the outer diameter (OD) of the cable sheath.

2 Experimental Setup

2.1 Pulse Generator

The tests of the pulse cables were performed using a high-current, all-solid-state pulse generator for magnetoforming at the Fraunhofer Gesellschaft (FhG) Institute for Forming Technology IWU at Chemnitz, Germany [1], [3]. The pulse generator has been developed by Siemens [2] and built by Highvolt GmbH, Dresden, Germany, and has the following electrical parameters:

capacitance	450 µF
charging voltage	2.5 … 21 kV
pulse energy	1.4…100 kJ
pulse current	20…200 kA_p nominal
	40…400 kA_p short circuited
pulse duration	100 µs typ.
pulse reprate	0.5 min^{-1}

The pulse generator (Figure 1) allows for a wide range of operating parameters and is used in a short-circuit mode in these experiments, as the short-circuited cable under test has a low impedance as compared to the internal generator impedance. The transmission line connecting the experiment and the pulse generator consists of a bundle of 6 parallel cables (see below) in order to reduce the transmission line impedance to an acceptable level.

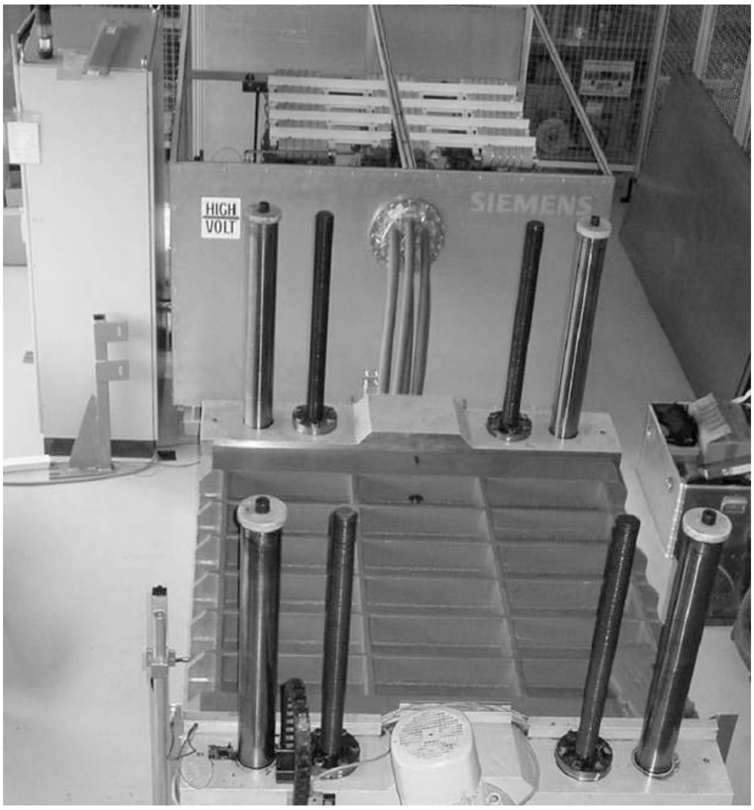

Figure 1: *Photograph of the pulse generator installed at the FhG IWU, Chemnitz, Germany. In the foreground the workstation with the vertically moveable mounting plate for the experiment can be seen.*

2.2 Coaxial Cable Test Setup

For the pulse generator installed at the FhG IWU Chemnitz, a mechanically rather stiff, high impedance high voltage cable of ca. 45 mm outer diameter (OD) has been used as a flexible transmission line. Its advantage is its high DC voltage capability of 200 kV, the large diameter of its outer conductor of 39 mm, and a large copper cross section. Its disadvantages are the stiffness, resulting in a large bending radius of >60 cm, and its high impedance; the specific cable inductance amounts to ca. 270 µH/m, resulting in a total TL inductance of 90 nH for the cables only. In the following, the test of an alternative medium voltage coaxial cable from Draka (Figure 2) (Draka NTMCWOEU Feltoflex 10 kV, 1x35/16, DC test voltage 42.5 kV, OD 24.5 mm) is reported. The diameter of the outer conductor is 17 m; the specific inductance is only 150 nH/m, and the cable is considerably more flexible than the cable originally used for the pulse generator.

The 110 cm long cable is fixed to the mounting plate of the magnetoforming workstation with a pair of V-shaped clamps (Figure 3), and the deformation of the cable caused by the magnetic pressure of the current pulse is measured in a clear section between the two clamps. On one side, the inner conductor of the cable is connected to the hot side of the cable bundle termination, while the outer conductor is connected to the ground side of the cable bundle. At the other side, the cable-under-test is short circuited by directly connecting the copper wire strands of the outer conductor to the inner conductor.

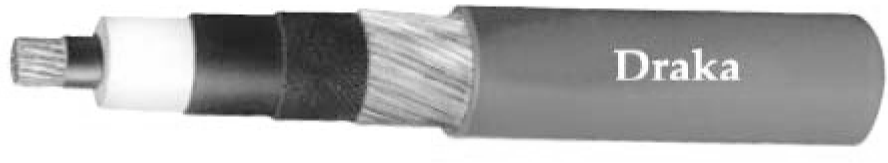

Figure 2: *Photograph of the Draka cable under test.*

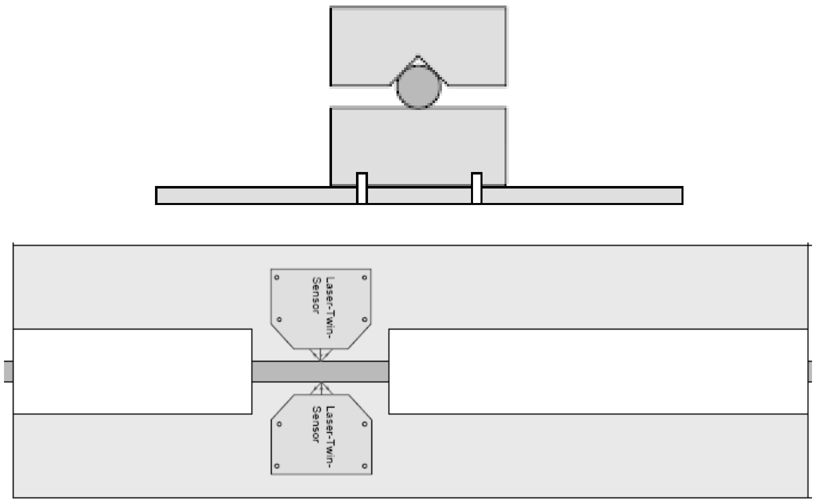

Figure 3: *Schematic drawing of the cable fixture during the experiments.*
Top: end-on view of the cable in the V-clamps; bottom: top view of the setup showing the clear section between the two clamps used to measure the cable deformation during the tests.

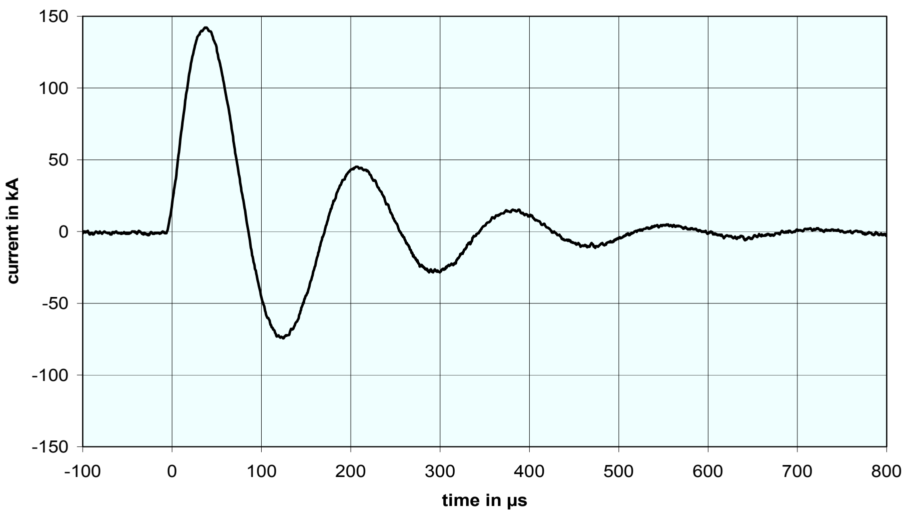

Figure 4: *Current pulse shape for a peak current of 142 kA.*

The cable is exposed to damped sinusoidal pulses of varying amplitude (Figure 4).

2.3 Diagnostics

The cable is clamped to the lower side of the mounting plate and viewed from below (Figure 5) using a high-speed video camera at a frame rate of 9000 fps (frames per second).

Figure 5: *Cable-under-test clamped to the mounting plate, illuminated with a cold-light lamp, and observed with a high-speed video camera.*

The spatial resolution of the video camera is 35 µm per pixel in the radial direction of the cable. At a frame rate of 9,000 fps, the time between frames is 111 µs, which is longer than the main current pulse. Therefore, the test system does not resolve the true dynamical movement (radial deformation) of the cable sheath during the current pulse, and only maximum values are used for further evaluation of the cable.

In order to determine the permanent cable deformation, the cable diameter was measured before and after each shot with a calliper. The absolute accuracy is comparable to that of the video camera measurements, and is of the order of 30...40 µm.

3 Experimental Results

The experimental results are summarised in the following graphs. Figure 6 shows the result from the video camera measurement, revealing that the dynamical deformation amplitude of the cable (blow-up) is of the order of 0.9 mm at the highest current of 142 kA_p. The long-term dynamical deformation is around 0.6 mm, while the permanent deformation caused by this shot is only 0.4 mm as determined from a calliper measurement (c. Figure 7). Permanent (non-reversible) cable deformation (expansion) starts above 60 kA peak current, indicating a permanent loss of the binding strength between outer conductor and cable dielectric at and above these current levels. Above a peak current of 120 kA, this expansion becomes noticeable growing to several hundred microns per pulse.

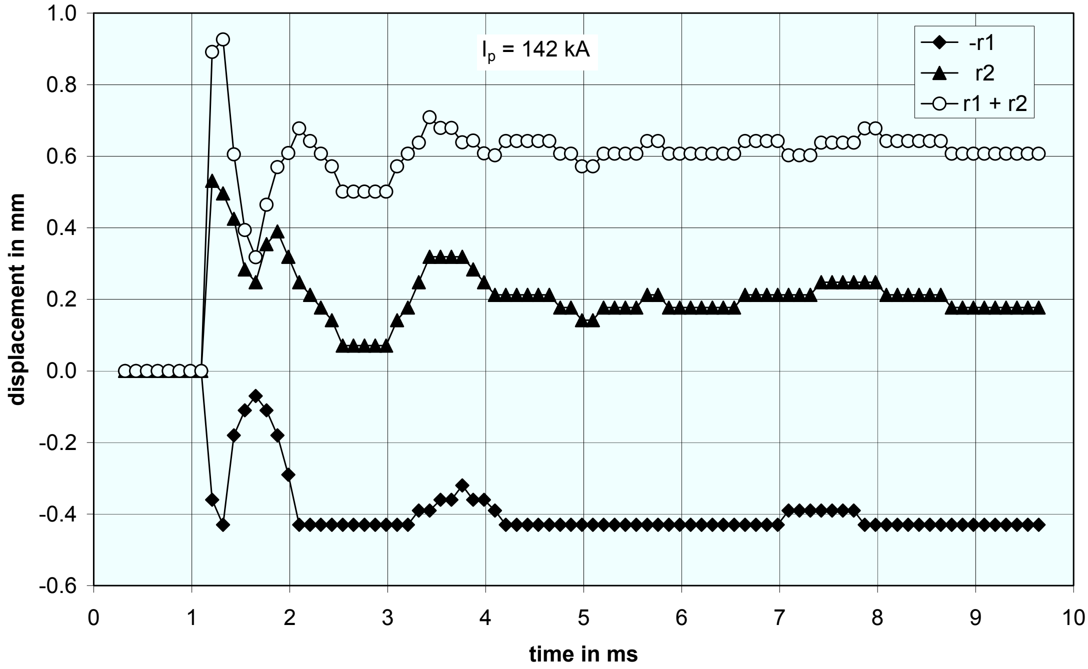

Figure 6: *Draka cable, dynamical deformation from high-speed video camera measurement, for a peak current of 142 kA (c. fig. 4).*

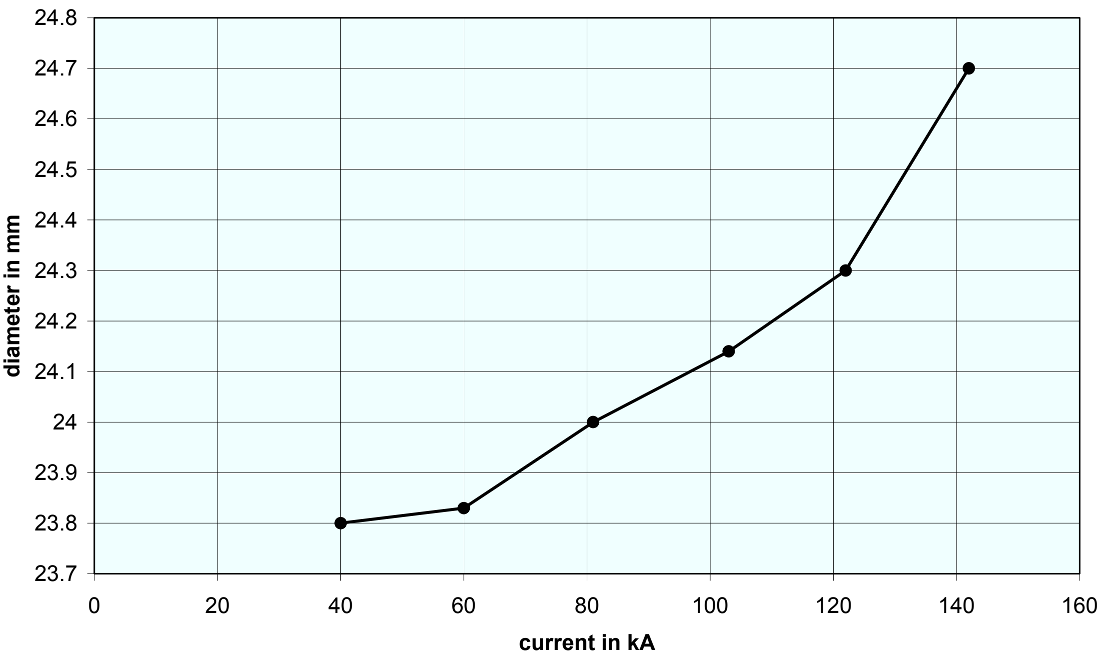

Figure 7: *Calliper measurement of the diameter of the Draka cable as a function of the current pulse amplitude after exposure to single pulses of increasing amplitude.*

4 Discussion

The experimental results as well as the calculation of the magnetic pressure leading to the observed cable expansion are summarised in figure 8.

The magnetic pressure inside a coaxial cable is calculated according to eq. 1:

$$p_{mag} = \frac{\mu_0 I^2}{8\pi^2 r^2} \qquad (1)$$

where p_{mag} is the magnetic pressure between inner and outer conductor; μo is the permittivity of space; I is the momentary current; r is the effective radius (≈ inner contour) of the outer conductor.

Due to the small diameter of the Draka cable, the peak magnetic pressure amounts to ca. 8 bar at a peak current of 60 kA, and increases to over 45 bar at currents around 140 kA. Obviously, the threshold pressure for permanent damage to the cable sheath for this type of cable is of the order of 6...8 bar and should not be exceeded for an extended number of pulses if the cable is intended to survive thousands or even millions of pulses. Short-circuit phenomena, on the other hand, should be rare events in a production unit, whence the short-circuit load capacity of the cable can be designed to be in the range of over 100 kA to 120 kA.

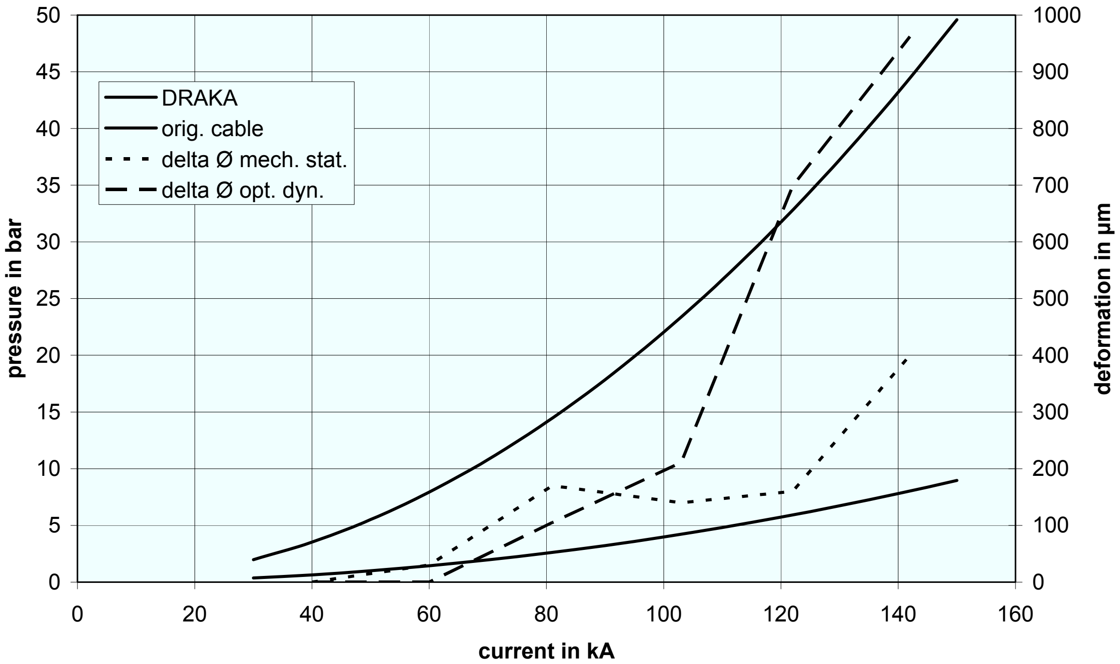

***Figure 8:** Calculated magnetic pressure inside coaxial cables ("DRAKA": cable used in these experiments (upper full line); "orig. cable": cable used for the connection between magnetoforming pulse unit and the experiment (lower full line); c. figure 1) and reversible ("opt.dyn.", dashed line) and non-reversible ("mech.stat.", dotted line) diameter change per pulse of the Draka cable as a function of the pulse current amplitude.*

The magnetic pressure as calculated for the original cable used in the magnetoforming unit at FhG IWU is shown as the lower curve in figure 8. Owing to its larger outer conductor diameter, the magnetic pressure inside the cable is considerably lower than that of the Draka cable at the same current; assuming a similar threshold pressure for permanent diameter change (i.e., a similar strength of the outer cable sheath), a single cable is able to carry pulse currents of up to 100 kA without deterioration, and should be able to survive up to 200 kA_p for a limited number of pulses (i.e., in short-circuit events on the load side).

5 Conclusions

We have characterised the pulse current capability of a coaxial medium voltage cable in the current regime of 40 kA to 140 kA. Dynamical and static measurements of the cable deformation (expansion) have shown that a save operating range can be identified where permanent cable deformation is negligible, as well as a current threshold has been found above which a permanent damage of the cable has to be taken into account. Below this threshold, we assume that the cable can be used for a large number of current pulses, i.e. in commercial applications of magnetoforming apparatus, while above this threshold the cable can survive only a few rare events like short-circuit loads caused by a faulty load.

The maximum pulse current allowable for a specific cable mainly depends on two characteristics, namely, the strength of the outer conductor and cable sheath, and the outer conductor diameter. For a specific medium voltage cable, we have found a threshold of the order of 6 to 8 bar of the magnetic pressure above which a permanent, non-reversible deformation (expansion) of the cable can not be avoided. Assuming that similar cables have similar properties, the results found in this work can be used to safely design flexible, long lifetime, high voltage, high current connections for pulsed power applications requiring high current amplitudes and a large number of pulses at the same time.

References

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