Experimental study of a helical coil operating mechanism for future switchgear applications

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***Abstract* — A key challenge for future switching technologies, especially in the context of the substitution of the strong greenhouse gas sulphur hexafluoride and the ongoing development of DC grids, is the increase of the contact opening velocity within switching devices. Thus, in this contribution a compact helical coil operating mechanism is developed and first experimental investigations are performed to characterize the accelerating and breaking performance of the mechanism. The helical coil arrangement is supplied by currents up to values of several kilo-amperes and the movement of the mechanism is analyzed.**

***Keywords* — operating mechanism; circuit breaker; helical coil**

I. Introduction

The replacement of the strong greenhouse gas sulphur hexafluoride and the emerging installation of multi-terminal HVDC grids lead to significantly changing requirements for future switching devices. On the one hand, the application of alternative insulating and arc quenching gases requires higher opening velocities of the contacts to compensate the reduced dielectric strength of these gases. On the other hand, fast switching devices are needed due to the fast increase of the fault current in DC grids [1,2].

In this contribution a compact helical coil operating mechanism is set up for replacing conventional mechanical spring drives in circuit breaker and switching applications. The total stroke is selected to match typical contact distances in state-of-the-art gas-insulated switchgear. Nevertheless, the operating principle can be easily extended to higher moving distances. In order to achieve an intrinsic breaking effect, the winding direction of the stator is reversed after half of the moving distance.

In a first approach, the operating mechanism is tested in the high current part of a synthetic test circuit with sinusoidal current. The initial position of the sliding anchor on the stator is varied to experimentally determine the acceleration and breaking performance of the operating mechanism. Furthermore, the amplitude of the sinusoidal test current is varied up to values of several kilo-amperes. The movement of the anchor is observed by measurements of the travel curve and video camera recordings. In addition, the wear of the stator windings as well as the sliding contacts of the anchor are investigated yielding a statement with regard to the durability of the operating mechanism.

II. Physical Basics

In a first step the basic theory behind the principle of electro-mechanically moving operating mechanisms is described in this section. The evaluation of the magnetic force between two current carrying coils is closely related to the calculation of their mutual inductance and the energy stored in it. This energy is equal to the product of their mutual inductance M and the amplitudes of the currents in the coils. As the same current flows through each winding of the coils, the attractive or repulsive magnetic force in any direction is proportional to the spatial differential coefficient of the mutual inductance M. Thus, the magnetic force may be calculated by simple differentiation in any case where a general formula of the mutual inductance is given as a function of the coordinate along which the force is required [3]. Assuming a coaxial construction, this results in

$$F = I_1 \cdot I_2 \cdot dM / dz \qquad (1)$$

where I_1 and I_2 are currents of two coils, M is their mutual inductance and z is the generalized coordinate. The magnetic force has only an axial component since their coils are coaxial. In order to apply equation (1) to the real geometry, the mutual inductance has to be expressed as a function of the generalized coordinate z which represents the axial coordinate. An appropriate choice is to take the axial displacement between the centers of the coils [4].

III. Mechanical Construction

Fast mechanical switching, e.g. as required in future DC grids, means to store a large amount of energy and converting it into movement in a short period of time. Electromagnetically operated systems are able to fit those requirements. In this context a compact helical coil operating mechanism represents a good first approach for an easy realization of a fast and controllable linear accelerator [5, 6].

The function of the helical coil approach followed in this contribution is shown in Fig. 1. The fixed stator coil as well as the moving anchor coil are energized by a current flowing in the same winding direction. Thus, two magnetic fields are generated by the anchor and stator windings, indicated by two magnets with north- and south-pole in Fig. 1. Since the current of the anchor and the stator are equal, the magnetic force in equation (1) can be adjusted by the value of the current or the

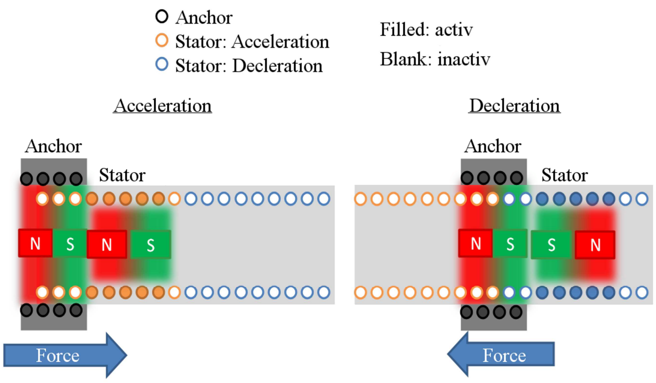

Fig. 1 Basic function principle.

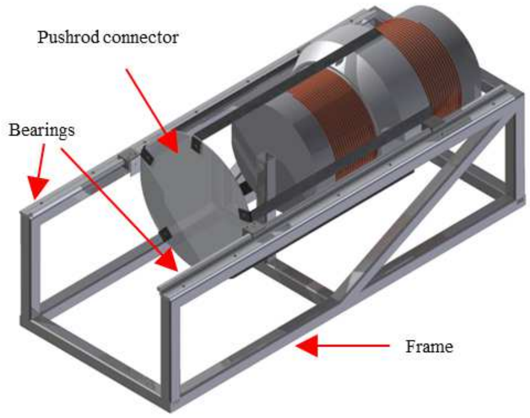

Fig. 2 General view of Prototype.

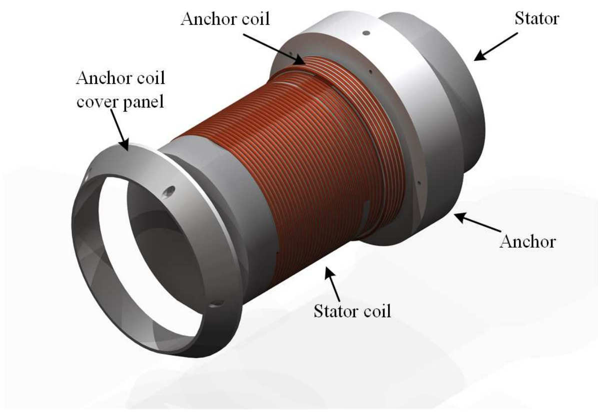

Fig. 3 Setup of anchor and stator.

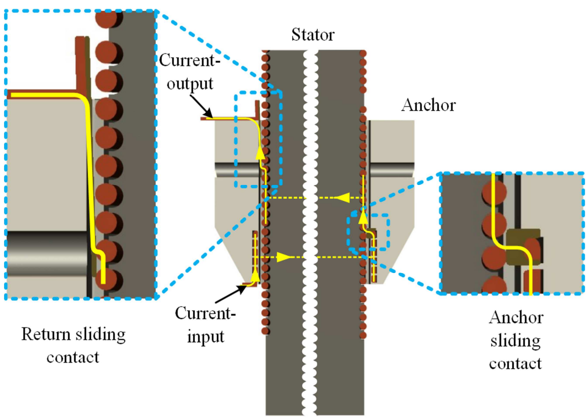

Fig. 4 Sectional drawing with sliding contacts.

mutual inductance. The mutual inductance mainly depends on the linked magnetic field flux, which for example increases with more active windings. During the acceleration, the anchor gets pulled by the magnetic force of the current-carrying part of the stator. As soon as the anchor gets close enough to the deceleration section of the stator the reversed winding direction results in a reversed and therefore breaking magnetic force.

Based on this basic functional principle a prototype of a helical coil operating mechanism is constructed according to Fig. 2 and 3. The inner stator is fixed as already explained above, while the outer anchor gets moved by the magnetic force. The anchor is mounted on bearings within a solid frame made of steel and is additionally equipped with a fixture for a driving rod considered for connecting the operating mechanism to a circuit breaker model in future investigations. The input and output connections for the infeed of the test current are fixed on the anchor. The current feed of the stator windings is realized by sliding contacts made of copper in a first approach (cf. Fig. 4). This ensures that a constant number of stator windings carry the current. Additionally, it is possible to decelerate the anchor's movement automatically by simply reversing the stators winding direction after half of the stator distance.

IV. SYNTHETIC TEST CIRCUIT

In order to generate a test current for the helical coil operating mechanism, the high current part of a synthetic oscillating test circuit typically used for characterizing the interruption capability of circuit breaker models is applied. The equivalent electric diagram is shown in Fig. 5. Before the experiment is carried out, the device under test (DUT) is installed. The auxiliary breaker (AB) is closed and the capacitance $C_T = 25$ mF is charged to their preassigned charging voltages, respectively. The high current capacitor C_T is charged up to voltages of 1 kV and then connected in series with the $L_T = 400$ µH inductance and the prototype.

Closing the making switch (MS) initiates a high sinusoidal current with a frequency of approximately 50 Hz, stressing the helical coil operating mechanism. After one or two half-oscillations the test current is interrupted by the auxiliary breaker.

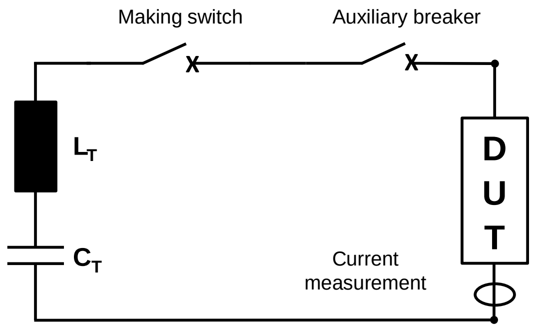

Fig. 5 Synthetic test circuit. The sinusoidal test current through the device under test (DUT) is initiated by the making switch and interrupted by the auxiliary circuit breaker.

V. Results of the Experimental Tests

In total 12 measurements are performed with the helical coil operating mechanism in a first approach with current amplitudes up to several kilo-amperes. All runs with the prototype are carried out without mechanical load, since the purpose of the experiments is to examine the moving behavior of the prototype described in section III. A Rogowski coil CWT 300B is used to measure the current and a roller is attached to the anchor which runs above a foil potentiometer. By measuring the change of the resistance, the position or the travelled distance of the anchor can be determined.

In the following section one experimental test including an accelerating and a breaking operation is described in detail. A detailed view of exemplary measurement data is given in Figure 6. It shows the current, the moving distance and hence resulting velocity over the time. During the experiment, the positive current half wave amplitude reaches I_{peak} = 7.4 kA while the negative amplitude obtains I_{peak} = -5.5 kA and the anchor travels over a distance of 8 cm. The observed negative velocity at the beginning of the first current half waves results from the repercussions of the current-free stator parts. Due to Lenz's law the direction of the induced currents flow is opposite to its source and hence the occurring force direction is inversed to the force described by equation (1). For the other experimental investigations, similar results are obtained. Overall, the measurement data shows, that the implemented helical coil mechanism is able to accelerate the anchor up to a speed of 8 m/s and afterwards decelerate it again.

In order to additionally illustrate the general mechanism of the switchgear prototype, Fig. 8 shows six snapshots of a video taken by a high speed camera during an experiment with two generated half waves. The simplifying longitudinal view of the realized helical coil mechanism below these snapshots illustrates the actual position of the anchor on the stator's acceleration or deceleration section. Furthermore, the featured current time curve indicates the given point of time. During the movement of the anchor copper grease - used for the lubrication of the stator windings - evaporates due to arcing during current commutation at the sliding contacts. This effect should be reduced in future investigations by adaption of the prototype design.

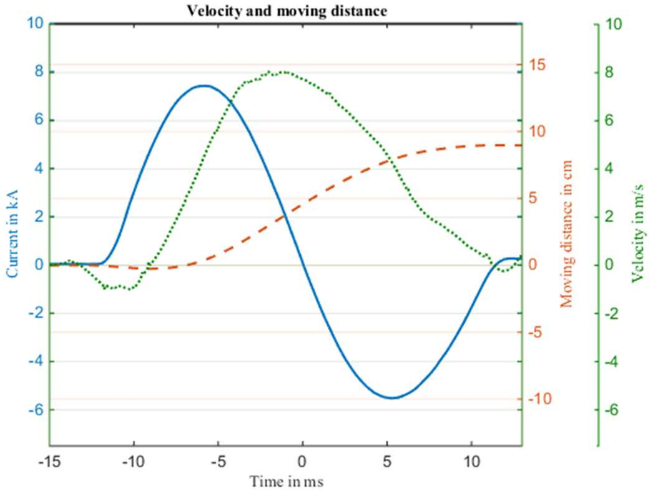

Fig. 6 Applied test current and resulting travel and velocity curve of the device under test from one exemplary measuerment.

VI. Mechanical Wear

The arcing due to current commutation at the sliding contacts and the stator windings observed during the experimental investigations also leads to wear of the sliding copper contacts as well as the stator windings. As depicted in Fig. 7, arcing marks occur especially at the sliding contacts of the anchor (left image) and at the transition point, where the winding direction of the stator is reversed for achieving an intrinsic breaking effect (right image, red marking). Additionally, the use of copper grease prevents strong wear of the windings on the rest of the stator, as it can be observed in the yellow marked region in the left image of Fig. 7. A future option to reduce the wear and to increase the endurance of the sliding contacts is the use of tungsten-copper instead of copper.

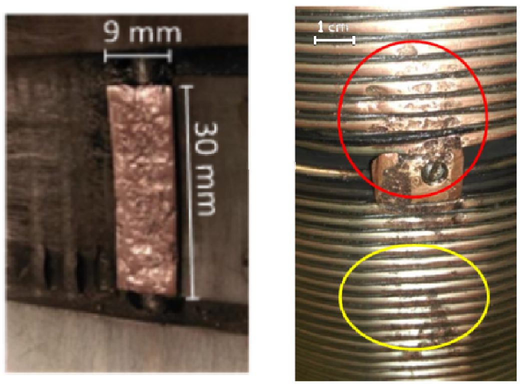

Fig. 7 Contact wear at the sliding contacts (anchor, left image) and windings(stator, right image)

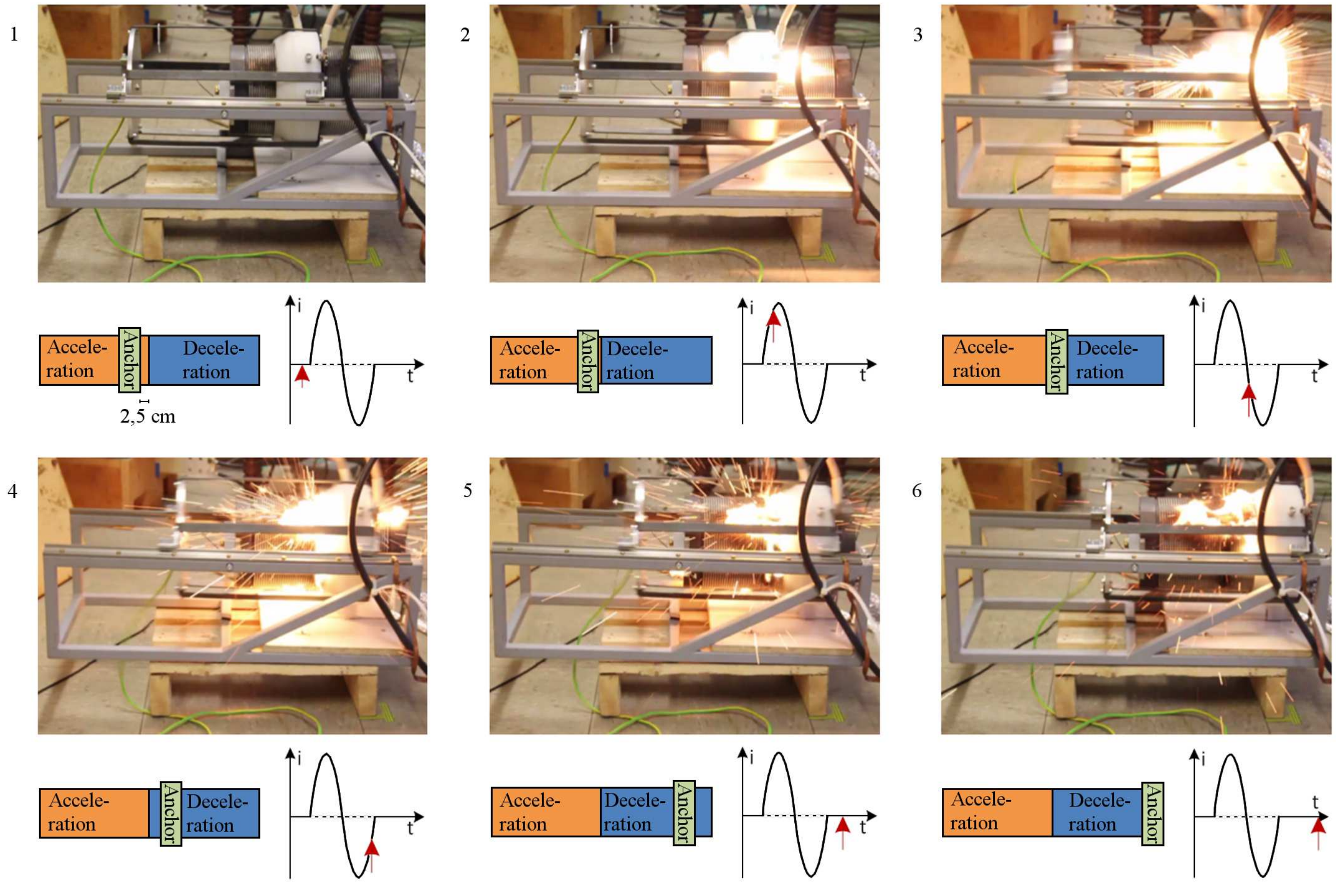

Fig. 8 High speed camera recordings of the movement of the test device.

VII. Conclusion

In this contribution an electro-magnetic operating mechanism was built based on the helical coil principle. The prototype was successfully tested in a synthetic test circuit and reached velocities up to 8 m/s with current amplitudes up to 7…8 kA. The experimental tests show, that for future investigations the durability of the sliding contacts needs to be improved, e.g. by using tungsten-copper material. In addition, a compact and modular power source for the operating mechanism should be developed.

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