Improving GIS Disconnectors for Future HVDC Applications

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Abstract—The use of standard HVac disconnectors for bus-transfer switching in future HVdc gas insulated switchgear (GIS) has been demonstrated successfully in past research through simulation and testing. Prolonged arcing times through reignitions caused by high frequency harmonics as well as the proposed extension of GIS disconnector switching cases, however, create an HVdc-specific demand for more advanced disconnector concepts capable of withstanding higher switching stresses and increased recovery voltages. A spring-loaded disconnector designed for use in HVac mixed technology switchgear (MTS) was found to shorten the time to first current zero through an accelerated increase of the arcing voltage compared to standard disconnectors. Despite its increased switching performance, the reignition characteristics of this fast-acting disconnector were found to largely follow the previously established extinction criterion, which enables further simulation of similar technologies for HVdc applications. To additionally combat the issue of contamination of HVdc GIS by electrode erosion products, a prototype disconnector was improved using permanent magnets to evoke arc rotation. Erosion tests in air have shown an effective reduction of electrode erosion for long arcing times at currents typical for disconnector switching while bus-transfer tests revealed promising enhancements of the reignition behavior.

Index Terms—HVdc, disconnector, bus-transfer, current-interruption, gas insulated substations, arc rotation

I. INTRODUCTION

GAS insulated switchgear (GIS) for HVdc and its associated phenomena have been the focus of research and development efforts for more than thirty years, with a special interest in gas and solid insulation as well as their interfaces [1]. Despite the advantages of GIS, such as greatly reduced space requirements and resistance against contamination, only very few installations exist today [2], [3]). One application which could particularly benefit from these advantages is the connection of large scale offshore wind projects to multi-terminal HVdc (MTdc) grids, due to the high cost of platform space and the benefits of HVdc submarine cables [4]. After decades of research (reviewed in [5]), the announcements of commercially available HVdc circuit breakers by manufacturers [6], [7] and their recent integration into one of the first MTdc grids in Zhoushan [8], [9] mark the achievement of one of the key enabling factors of MTdc grids. Compared to circuit breakers, disconnectors

Fig. 1. Simplified equivalent circuit diagram for bus-transfer switching, in which the disconnector is modelled as a current and time dependant voltage source u_{DS} as used in prior investigations [11], [13], [14].

face lower requirements in terms of switching power but are nevertheless of critical importance for substation and grid operation. Their applications in HVdc converters have been well documented [10], however, MTdc-specific research of requirements and available technology for use in substations remains rare. The use of disconnectors to transfer load currents between parallel conductors such as bus bars of a substation or submarine cables in an MTdc grid has been investigated by Kanngiesser [11], Vinson [12] and the authors [13]. The findings of long arcing times without current zeroes for large inductances and high harmonic contents leading to multiple reignitions present dc specific challenges, which have to be investigated further and which can be mitigated by improved disconnector designs.

II. SCOPE OF RESEARCH

In HVac GIS, disconnectors have a long history of operation at high reliability rates [15], thus it is sensible to start with established designs and developments when studying requirements and proposing changes for HVdc specific disconnectors. In prior research on the fundamentals of bus-transfer switching in HVac [14] and HVdc GIS [13] employing widely used GIS disconnectors with slow-moving and unblown electrode systems, the authors have identified a correlation between the instantaneous recovery voltage u_{RV} and the predicted arc voltage u_{arc} at a current zero at time t_0 , which ensures an extinction of the switching arc:

$$u_{RV}(t_0) \leq u_{arc}(t_0). \quad (1)$$

This extinction criterion is based on the finding that in such disconnectors, the conditions for reignition at current zero are almost always assured, so that extinction is only certain if the circuit is unable sustain the arc voltage further.

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For this bus-transfer switching case, the circuit consists of two different lengths (d_1, d_2) of substation bus which can be modelled as a parallel connection of two inductances (L_1, L_2) and resistances (R_1, R_2) as shown in Fig. 1. The switching current i_2 can be simulated for any source current i_S by numerically solving the resulting differential equation as long as the arc voltage function is known and the bus properties (L', R') as well as the bus lengths are given. While current zeros occur naturally in ac bus-transfer, they have to be generated by the arc voltage in dc cases. The time to first current zero in cases with harmonic-free dc current have been calculated to be on the order of 5 ms at a pre-switching current of 2 kA for typical configurations of GIS. With increased size (d_1, d_2), voltage level (L') and pre-switching current ($i_S \cdot d_1 / (d_1 + d_2)$), these times become longer [13].

Another potential application of HVdc disconnectors, which can be modelled by the equivalent circuit diagram of Fig. 1, is that of line transfer under load as simulated by Vinson in [12]. Their simulations found that even a disconnector with substantially faster moving electrodes resulted in arcing times two orders of magnitude longer than for bus-transfer.

The erosion of electrode surfaces by such switching arcs has been studied extensively in the past [16]–[18]. The combination of electrode erosion and mechanical abrasion of moving parts leads to the production of solid particles inside GIS vessels, especially in disconnectors. Resulting effects such as elevated charge transport in the insulating gas and along insulator surfaces [19], lowered dielectric withstand [20], [21], and particle movement [22]–[24] have been well researched, especially for HVac system under dc stress (i.e. trapped charges) and specifically for HVdc systems. Therefore, reducing the production of particles in disconnectors sustaining repeated operation is an important development goal. In the following, two methods to achieve this goal are evaluated experimentally: A commercially available fast-acting HVac GIS disconnector used in mixed technology switchgear (MTS) and a purpose-built disconnector testbed with variable opening speed using permanent magnets for magnetic arc driving in atmospheric air.

III. TEST SETUP AND EVALUATION

The complete test circuit used to investigate both types of disconnectors is shown in Fig. 2. The source current is provided by the flexible pulsed dc source (FPDCS), which has previously been used for research in HVdc circuit breakers among other applications [25]. FPDCS is composed of three identical buck converter modules (M_1, M_2, M_3) featuring individually adjustable inductances (L_1^M, L_2^M, L_3^M) connected in parallel. Each module delivers up to 1 kA of pulsed current at switching frequencies between 0.1 kHz to 10 kHz. A detailed review of the working principle, capabilities and applications was recently presented by the authors [26]. The full bus-transfer loop consists of two parallel GIS bus equivalents (L_1, R_1 and L_2, R_2), which can be adjusted to represent between 15 m to 1360 m of typical 420 kV HVac GIS. The same configuration has been used successfully to study the fundamentals of bus-transfer of slow-moving disconnectors

Fig. 2. Equivalent circuit diagram of the flexible pulsed dc source connected to the full bus-transfer loop via an adjustable source resistor and low pass filter including all points of voltage and current measurements (blue).

in ac [14] and dc [13]. For the investigation of disconnectors at higher recovery voltages, a low pass filter (R_F, C_F) was implemented, mitigating high frequency oscillations, which are otherwise excited by large changes of the current gradient between the bus-transfer inductances and parasitic capacitances of the FPDCS modules. By blocking frequencies above 500 kHz, this filter also creates a predictable low pass characteristic apparent especially during large step changes in the recovery voltage across the open disconnector.

The measurements captured during each test include the absolute voltages on either side of the disconnector (u_{DS}^+, u_{DS}^-) and on either side of the entire bus-transfer loop (u_{LP}^+, u_{LP}^-) using high-frequency 1:100 dividers. The currents i_1, i_2 and i_S are measured using current transducers according to the HOKA principle [27] at frequencies between 0 Hz and 1 MHz. Additionally, high speed images at up to 200 kfps were captured during many tests. The evaluation of the measured data follows algorithms established for previous tests of slow-moving disconnectors [13], [14], [28]. Open-circuit (OC) tests, during which the disconnector remains in open position, are used to assess the recovery voltage and to tune the bus-transfer parallel inductance L_1 as well as the source resistance R_S . Short-circuit (SC) tests see the disconnector remain closed in order to tune R_1, L_2 and R_2 and to find a prediction for the pre-switching current distribution. Using these values, the current distribution between i_1 and i_2 as well as the recovery voltage u_{RV} can be calculated for any test, to aid in the manual evaluation of current zeros. As an additional benefit of the low pass filter, u_{RV} can be approximated for any point in time of any measurement using i_S^{LP} , a digitally filtered version of the source current i_S in combination with R_1 and L_1 calculated from OC measurements, according to the following

expression.

$$u_{RV}(t) \approx R_1 i_S^{LP}(t) + L_1 \frac{di_S^{LP}(t)}{dt} \quad (2)$$

IV. FAST-ACTING DISCONNECTOR: SETUP

In HVac MTS, air insulated buses are linked by gas insulated circuit breakers, disconnectors, and earthing switches, primarily to save space [29]. Disconnectors designed for this application are capable of withstanding up to ten times higher recovery voltages than GIS disconnectors, due to the larger substation dimensions and the increased inductance per unit length. One example of such a disconnector is presented in a 2013 patent [30] to have a spring-loaded opening mechanism inside the pressure vessel in order to create high opening speed. The accelerated contact opening causes a faster increase of the arc voltage compared to traditional, slow-moving disconnectors. In HVdc GIS, a higher arc voltage translates to a lower time to first current zero for a given configuration as well as an increased likelihood of fulfilling the extinction criterion of eq. (1) during bus-transfer, as previously simulated [13]. The disconnector used in this research is an ABB TK3S designed for application in 420 kV MTS substations. It closely follows the aforementioned patent. Due to its intricate electrode separation mechanism, the minimum electrode separation distance has been estimated by means of a FEM tool fed with the measured stroke in dependence of time. First, the electrode deformation during gliding and oscillation after release has been simulated with a structural mechanics module, with electrode pressures being formulated by the penalty method. Second, this mechanical solution has been post-processed, by means of an extrusion-function applied on one electrode side, defining the distance field in the vicinity of this electrode; minimizing it on the contour of the other electrode-side reveals the minimum distance between

the electrodes for every time-step. Clearly, the arc does not necessarily have to exhibit arc roots resulting simply from the shortest distance between the electrodes. Especially, as there is lateral movement of the electrodes, resulting in arc elongation if the arc roots do not constantly follow the points of shortest distance between the two electrodes. Moreover, longer arcs tend to exhibit instabilities or protuberances, which elongate the arc column independent of the electrode distance, thus increasing the arc voltage further. The minimum electrode separation distance calculated using this method is shown in Fig. 3 (bottom left).

V. FAST-ACTING DISCONNECTOR: RESULTS

In order to simplify analysis and simulation of bus-transfer measurements using this disconnector as well as to verify the dynamic FEM simulations, a two-part polynomial fit was applied to the results of all tests. Arc voltages recorded at currents higher than 500 A were averaged over 0.1 ms segments and fit to a fourth order polynomial for the time of lateral movement phase (i.e. $t < 3.5$ ms) and a second order polynomial for the actual electrode separation at times larger than 3.5 ms. In Fig. 3 (bottom right) this fit is compared to all voltages recorded within 0.5 ms of a current zero, i.e. at low currents. It is evident, that u_{arc}^{fit} is a good estimation of the lowest arc voltage as a function of time. In order to estimate time to first current zero, u_{arc}^{fit} can be used as a function of voltage of time to simulate i_2 in the equivalent circuit diagram of Fig. 1. In Fig. 3 (top), the results of this estimation for varying combinations of bus-transfer loop and pre-switching current are presented. It is evident that the fast increase in arc voltage caused by the spring-based contact separation is effective at creating short first current zero times even for high currents and long bus-transfer loops, especially compared to traditional, slow-moving disconnectors. In order to analyze dc bus-transfer performance including reignitions of this particular fast-acting disconnector, more than 400 individual tests were performed using the circuit shown in Fig. 2. Each current zero was manually categorized as extinction of the switching arc or as one of the following three different types of reignitions:

- 1) *Immediate reignition*: Switching current crosses zero without any delay. Disconnector voltage is equal to arc voltage immediately before and after current zero. Total number evaluated: 337.
- 2) *Delayed reignition*: Switching current remains zero for some delay time before reignition. Disconnector voltage is equal to recovery voltage during delay, after a sudden change in recovery voltage arc voltage appears. Total number evaluated: 58.
- 3) *Charging reignition*: Switching current remains zero for some delay time before reignition. Disconnector voltage is equal to recovery voltage until it switches to arc voltage without a large change. Total number evaluated: 342.

While immediate reignitions were the default reignition type in previous analyses of slow-moving disconnectors in ac and dc conditions at comparably low recovery voltages, they have

Fig. 3. Top: Time to first current zero for harmonic free dc at varying combinations of pre-switching current equal to 80 % of i_S and total bus lengths $d_1 + d_2$. Bottom, left: Minimum electrode separation estimation based on dynamic FEM simulation. Bottom, right: Arc voltages averaged over a period of 0.5 ms before every current zero (u_{arc}^{meas}) and the two-part fit of data points at currents above 500 A (u_{arc}^{fit}).

been surpassed in frequency by charging reignitions in tests of the fast-acting disconnector. This new type of reignition is a direct result of the integration of the aforementioned low pass filter, which slows down step-changes in the recovery voltage. During charging reignitions, instead of immediate jumps between arc voltages of different polarity, the voltage across the disconnector changes from arc voltage towards the recovery voltage with an exponential time-constant of approximately $5\mu\text{s}$. Furthermore, the use of large L_1 in combination with high source current gradients influences behavior at current zero as well, as it leads to an interaction between the bus-transfer loop inductances L_1 and L_2 with

the source inductances L_1^M , L_2^M , and L_3^M . When i_2 is non-zero, the equivalent inductance of the full bus-transfer loop is approximately equal to L_2 , however, when no current is flowing across the disconnector, the inductance of the bus-transfer loop is equal to L_1 . If the difference of these two inductances is in a similar order of magnitude as the smallest source inductance, the change from non-zero to zero current can influence the source current gradient and thus the recovery voltage. The measured recovery voltage (u_{DS}) corresponds to zero current across the disconnector (i.e. L_1 as only load of the current source). However, the recovery voltage relevant for the extinction criterion of eq. (1) is that of a non-zero i_2 (i.e. L_2 as load inductance). Therefore, a pre-determined correction factor was applied to extinctions. For charging reignitions and delayed reignitions only the recovery voltages calculated immediately after reignition are used for the same reason.

The results of all evaluated current zeros are presented in Fig. 4. Most of the reignitions occurring at recovery voltages close to the arcing voltage are of charging type, due to the low pass filter's mechanism of slowing down small voltage steps. At recovery voltages more than approximately 200 V above the predicted arc voltage, immediate reignitions start to dominate. For most cases of delayed reignition, the recovery voltage at current zero is below the predicted arc voltage at that time, thus fulfilling the extinction criterion of eq. (1). However, after a short delay of up to $110\mu\text{s}$, a sudden change in the recovery voltage to a level otherwise associated with immediate reignitions leads to a delayed reignition. Therefore, the assumption that the conditions for reignition are present only at current zero has to be extended to some time after current zero. The majority of delayed reignitions have been found to occur within $50\mu\text{s}$ but delays of more than twice that duration have been recorded on rare occasions. For a conclusive characterization of mechanism and likelihood of reignition as a function of delay and voltage for this particular disconnector, more detailed measurements would have to be performed.

These findings are especially important for HVdc applications with high harmonic current contents and thus intermittently high recovery voltages, as well as for applications in which the total arcing time needs to be minimized by a rapidly increasing arc voltage. Fast-acting disconnectors built for use in HVac MTS, therefore, present a suitable starting point for the development of disconnectors addressing these HVdc-specific challenges.

VI. DISCONNECTOR TESTBED

Due to the limitations in variability of influencing factors imposed by a production disconnector, requirements for a specialized disconnector testbed were collected. The testbed was aimed at exploring dc-specific improvements to switching performance in an automated fashion with minimal changes to established disconnector mechanics:

- 1) Large range of opening speeds, adjustable without mechanical changes to electrode system of classic, slow-moving disconnectors, i.e. annular rings.
- 2) Use of common arcing electrodes of GIS disconnectors in a way that facilitates exchange between tests.

Fig. 4. Absolute recovery voltages of all current zeros recorded during tests of the fast-acting GIS disconnector categorized into different reignition types and extinction. Top: Overview of entire $|u_{RV}|$ range. Bottom: Zoom onto voltage range immediately surrounding u_{arc}^{fit} .

Fig. 5. Top-down view of the disconnector testbed with mounted electrodes and magnets in a single-sided arrangement [31].

- 3) Application of magnetic arc driving to reduce electrode erosion with minimal changes to contact system.
- 4) Good observability of switching arc from various angles by high speed camera.
- 5) Possibility to perform tests in ambient air as well as in pressurized gas vessels.

The realization of these requirements is presented in Fig. 5. The testbed is built using GIS disconnector-specific, annular tungsten-copper (80 % W, 20 % Cu) arcing electrodes of 94 mm inner and 128 mm outer diameter as shown in Fig. 6. These electrodes are fixed to cylindrical aluminium mounts by four screws each; concentric grooves allow precise orientation. The aluminium mounts are electrically isolated from a spring buffered mount on one side (fixed contact) and motor on the other side (moving contact) by a set of polyether ether ketone (PEEK) plates designed to bend less than 1 mm at maximum force. The opening speed requirements are fulfilled by a linear motor providing a maximum acceleration force of 1120 N, capable of peak speeds of 4 m s^{-1} when pulling the entire moving contact. To increase the initial speed of electrode separation without the use of abrasion-prone sliding electrodes, a spring buffered mount with an end stop was constructed (cf. left side of Fig. 5). This mount allows the fixed contact to travel with the moving contact for the first few millimeters before electrode separation occurs at up to 1.25 m s^{-1} . The entire testbed is built to be small enough to fit inside a typical 550 kV GIS vessel to allow tests in pressurized gases in the future. For the scope of this research, however, tests were performed in ambient air exclusively.

The use of transverse magnetic fields to continuously move an electric arc on the electrode surface has been studied regularly in the past [32], often with the goal of reducing localized heating and electrode erosion [33]. It has also been suggested as a method to improve switching performance of disconnectors [34]. The majority of published concepts rely on one or more coils in the vicinity of the arcing electrodes to create a transverse magnetic field using the switching current. The resulting Lorentz force acting on the arc is thus proportional to the square of the switching current, which can make low-current switching cases such as bus-transfer difficult. Additionally, adding a coil powerful enough

Fig. 6. Frontal view of the fixed contact showing the annular electrode as well as the polycarbonate housing of the permanent magnets and the arc rotation detector in the center.

to generate a transverse magnetic field across a potentially long opening distance can represent major design challenges. To avoid both of these drawbacks, the generation of a strong transverse magnetic field using permanent magnets positioned in the close to the electrodes was evaluated. In magnetostatic finite element method (FEM) simulations, numerous shapes and magnetizations of commercially available permanent magnets were evaluated before arriving at cylindrical neodymium magnets of 40 mm height and 10 mm diameter with an axial remanence of 1.26 T to 1.29 T. An outer ring made up of 36 magnets and an inner ring of 20 magnets were simulated to be either placed around the electrode of the fixed contact (i.e. single-sided) or on either of the two electrodes (dual-sided) as shown schematically in Fig. 7. In these configurations magnetic fields transverse to the arc with a large degree of radial and angular homogeneity resulted. In Fig. 8, the transverse magnetic field B_r simulated at both electrode surfaces as well as the middle of the opening distance are plotted as a function of the opening distance. It is apparent, that the single-sided arrangement is well suited for applications which rely only on short opening distances as the magnetic field at the surface of the moving electrode decays rapidly after only a few tens of millimeters. This fact was verified in preliminary tests which demonstrated that transverse magnetic fields below 50 mT on the electrode of the moving contact lead to sticking of the arc root. Therefore, all tests presented herein were performed using the dual-sided arrangement.

To fix the cylindrical permanent magnets in place while also

Fig. 7. Schematic view of the single-sided (left) and dual-sided (right) mounting options of the permanent magnets on the fixed and moving contacts. Direction of movement is indicated by dotted arrow. Cylindrical magnets are illustrated as magnetic north (red) and south (green) poles.

Fig. 8. Simulation of the radial magnetic field at the electrode surfaces of the fixed contact (B_r^{fixed}) and moving contact (B_r^{moving}) as well as halfway between the two contacts ($B_r^{d/2}$) for single-sided (left) and dual-sided magnet arrangement (right) for a straight arc with its roots in the middle of the annular electrode rings.

providing dielectric insulation from the electrodes and thermal insulation from the arc, two polycarbonate housings were additively manufactured. The larger of the two can be seen mounted on the fixed contact in Figs. 5 and 6. Through a matrix of holes on both electrodes, the offset of the magnet housing relative to the electrode surface can be adjusted in steps of 1 mm. To be able to measure the rotational speed of the arc during each test, a detector (referred to as arc rotation detector) consisting of eight high frequency hall-effect sensors with integrated constant current sources and amplifiers was built to fit inside either of the electrodes as shown in Fig. 6. The sensors transduce magnetic fields perpendicular to their surface at 50 mV mT^{-1} . Thus, each sensor was positioned so as to register the passing of the arc as a voltage peak while being largely undisturbed by the background magnetic field caused by the permanent magnets. A total of eight hall-effect sensors were placed at 45° from each other in order to achieve a high spatial resolution. In post-processing, a peak detection algorithm determined the points in time at which the arc passed by each of the eight sensors, thereby merging all eight voltage signals into one measurement of arc speed of time. Due to the location of the the arc rotation detector, the measured arc speed corresponds to the speed of the arc root on the surface of the electrode within which the detector is mounted.

VII. ARC ROTATION IN AIR: SPEED & VOLTAGE

In Fig. 10 two tests at either limit of the opening speed of the testbed are presented with the magnets in the dual-sided arrangement for a constant current of 2.5 kA. These tests were performed using FPDCS with the testbed directly connected as load, i.e. without any bus-transfer loop components (c.f. Fig. 2). It is clear from the electrode separation distance measured by the linear motor itself (d_{meas}), that the maximum available pulling force of the linear motor is only enough to reach the desired 4 m s^{-1} towards the end of the fast opening test while the test at 0.1 m s^{-1} exhibits a constant speed over the majority of the arcing time. A delay of 6 ms before the start of arc rotation was found to be fairly consistent, independent of switching current and opening speed. The deviations in measured arc voltage (u_{DS}) from the fit ($u_{\text{arc}}^{\text{fit}}$) are most likely

caused by temporary elongations of the arc column. From high speed images as well as voltage measurements, it can be concluded that the magnitude of these temporary elongations increase with opening distance and decrease with switching current. This property is especially beneficial for switching cases such as bus-transfer, in which an increase in arc voltage accelerates the decrease of the switching current.

The measured arc speeds (m s^{-1}) in the example of Fig. 10 are drawn as a band of possible values: Since the the hall-effect sensors measure in rotations per time (rad s^{-1}), the speed of the lower end of the band corresponds to the arc burning on the inner diameter of the electrode (v_{inner}), while the upper end corresponds to the opposite (v_{outer}). The acceleration phase of 10 ms only seen in the test with slow opening speed can be attributed to two phenomena: Firstly, due to the small opening distance, each rotation of the arc heats up the air between the two electrodes, decreasing the gas density until an equilibrium of heat transfer is reached [35]. Secondly, at arc lengths in the range of a few millimeters, electrode effects play a significant role in determining arc speed. This influence decreases at greater opening distances [32].

The results of a test series of arc speeds recorded at different

Fig. 9. Arc rotation speeds calculated at the middle of the annular electrodes based on the measured rotation frequencies, averaged at arcing times 10 ms to 15 ms (top) and 20 ms to 25 ms (bottom) for varying opening speeds v . d corresponds to the opening distance in the middle of each arcing time range.

Fig. 10. Comparison of two high-current tests at peak opening speeds of 0.1 ms^{-1} (top) and 4 ms^{-1} (bottom) and constant currents of 2.5 kA used to evaluate arc speed as a function of current. Legend in upper plots applies to both tests shown.

currents and opening speeds are shown in Fig. 9. The less than linear increase of speed with current can be attributed to the linear increase of Lorentz force with current, which is counteracted by aerodynamic drag growing with the square of the speed. Guile et al. [32] give a proportionality of $v \propto I^{0.4}$, while Szente et al. [33] found $v \propto I^{0.60}$. In the presented data it is also evident that arc speed decreases with opening distance. This is a result of the decreasing magnetic field of the permanent magnets acting on the arc column with increasing opening distance. The cited literature furthermore agrees that changes in the density of the cold gas surrounding the arc can be taken into account as $v \propto \rho_a^{-0.5}$, where ρ_a is the relative gas density. Therefore, the arc speeds of Fig. 9 gathered in ambient air are approximately five times higher than what would be expected in a typical GIS filled with SF_6 pressurized to 5 bar. A less precisely quantifiable effect of the ambient gas is the ability to react chemically with the electrode surface. Oxidation of electrodes has been shown to have a measurable influence on arc speed and on erosion (c.f. [17], [33]). When performing test series using the disconnector testbed, exposing electrodes contaminated with erosion products to air for extended periods led to a substantial increase in arc rotation speed.

VIII. ARC ROTATION: ELECTRODE EROSION

One of the major benefits of continuous arc rotation on large electrodes is the distribution of heat transferred into the electrode surfaces and thus the reduction of erosion of the electrode material. To quantify this reduction, the following five series of tests were performed for two sets of identical electrodes in air with magnetic arc driving and an opening speed of 0.1 ms^{-1} :

- 1) & 2) $25 \times 1.8 \text{ kA}$ for $50 \text{ ms} \approx 2.3 \text{ kC}$
- 3) & 4) $25 \times 1.8 \text{ kA}$ for $100 \text{ ms} \approx 4.5 \text{ kC}$
- 5) $20 \times 2.5 \text{ kA}$ for $100 \text{ ms} \approx 5.0 \text{ kC}$, c.f. Fig. 10

After each series, the arcing electrodes were removed and weighed individually on a scale with a precision of 50 mg . After the final weighing, anode and cathode were thoroughly cleaned in order to remove transferred and redeposited electrode material. The results of these tests are shown in Fig. 11. While the mass lost without magnetic arc driving increases steadily with cumulative charge, there is also a substantial amount of erosion product in the form of spherical drops on the cathode that were only removed after the last test. The total mass lost is 4.1 g , for a cumulative charge of 17.3 kC , i.e. an averaged erosion rate of $240 \mu\text{g C}^{-1}$. After the test series with magnetic arc driving no mass loss was detectable as the results were within the uncertainty of the scale used, i.e. 100 mg , resulting in a mass loss of less than 100 mg over 17.9 kC and an erosion rate of less than $5.6 \mu\text{g C}^{-1}$. Additionally, cracking of the electrode surface and emission of metallic particles was found to be non-existent on these electrodes except for a small region in which the arc preferentially remained stationary for the first few milliseconds of each test.

The difference between erosion is expected to be more accentuated in compressed SF_6 , as the arc root current densities in the presented tests (executed in air) revealed lower values than known from disconnector application in compressed SF_6 . Typical concepts to predict erosion balance energy fluxes such as radiation, electrode falls, evaporation and diffusive conduction into the contact bulk. Heat conduction into electrode and contact material increases with the arc root area, shifting the energy flux balance in the direction of lower erosion.

Typical arc root point current densities are about $j =$

Fig. 11. Measured mass loss during repetitive erosion tests at currents of 1.8 kA to 2.5 kA and arcing times up to 100 ms . Filled symbols represent the mass loss after thoroughly cleaning the surface of the contacts.

10^8 A m^{-2} in compressed SF_6 , whereas the densities in the current test have been a third of this value (i.e. increasing the root area by a factor of three). Furthermore, observations using a high speed camera revealed, that only about one third of the tests exhibited a stable, undisturbed arc during the test. One third of the arcs showed slight movement and another third strong, continuous movement during the test in air. Conversely, no such behavior was observed in the tests under compressed SF_6 , thus larger erosion rates are expected in compressed SF_6 conditions due to the increased localized heating of stationary arc roots.

A rough estimation of the impact of the larger arc root diameter is possible by assuming a spherical symmetric heating from the arc root into the material. By further assuming constant heat conduction and capacity of the electrode material (i.e. neglecting temperature dependency), the total heat conduction P_{cond} into the electrode material scales with the arc root radius r_{arc} according to

$$P_{\text{cond}} \propto \left(r_{\text{arc}} + \frac{r_{\text{arc}}^2}{\sqrt{\pi c_p \lambda t}} \right) \quad (3)$$

with the arcing time t , the specific heat c_p , and the thermal conductivity λ . Hence, the arc root enters linearly for long arcing time (stationary temperature profile) and quadratically at the beginning (transient temperature profile). Hence, the erosion rates measured in atmospheric air (c.f. Fig. 11) are expected to a factor of 1.5...3 higher under the condition of compressed SF_6 (with three time larger arc root current densities).

IX. ARC ROTATION: BUS-TRANSFER

In addition to the erosion tests, a number of bus-transfer tests were performed at opening speeds of 0.1 ms^{-1} using the same setup and evaluation methods as for the fast-acting disconnectors. The control tests without magnetic arc driving revealed substantial differences in reignition behavior to the previously studied GIS disconnectors of the same opening speed operating in compressed SF_6 . In some cases, the conditions for immediate reignition at current zero appeared to vanish faster, leading to extinctions at recovery voltages up to ten times higher than the observed arc voltage. This difference is likely due to the 27 times lower density of ambient air compared to pressurized SF_6 , which increases the mobility of the arc column and accelerates the diffusion of hot gas into the area surrounding the arc. Furthermore, delayed reignitions up to $500 \mu\text{s}$ after current zero at voltages in the range of 400 V to 600 V were recorded, most likely caused by the lower dielectric strength of hot ambient air compared to hot SF_6 and the superior cooling properties of the latter. Nevertheless, numerous immediate reignitions, charging reignitions and delayed reignitions were recorded at levels comparable to prior GIS tests.

With the permanent magnets mounted for magnetic arc driving, the bus-transfer results are split into two categories. For the initial few milliseconds in which the arc remained stationary at the point of inception, no change compared to the tests without magnets is apparent, i.e. reignitions occur

in the same manner at the same voltages. However, once arc rotation started, no more immediate or charging reignitions were registered. It can be assumed that the rapid movement of the arc leads to an efficient mixing of hot and ambient gas at current zero, thus rapidly eliminating the conditions favoring reignition. The same has been found for delayed reignitions in all but one case, even at voltages that were guaranteed to reignite the electrode gap without magnets. The one exception was recorded when a current zero occurred immediately after the start of arc rotation before a full rotation was completed. The switching arc reignited at the point of original arc inception instead of the position at current zero, most likely due to the localized heating occurring for 6 ms preceding the start of the arc movement. This change in reignition behavior represents a fundamental improvement of the switching capabilities for HVdc applications. Without reignitions at current zero (within reasonable voltage ranges), the time to first current zero automatically becomes the total switching time.

X. CONCLUSIONS

It has been shown with a combination of simulations and large test series that readily available HVac MTS disconnectors offer advantages over traditional slow-moving GIS disconnectors for MTdc switching cases such as bus-transfer. The fast increase in arc voltage over time leads to a short time to first current zero, even for extremely large sections of GIS at high currents, while also providing improved resilience against recovery voltages caused by current harmonics. Furthermore, an arrangement of widely available permanent magnets, which requires only minimal changes to proven disconnector designs, has been shown to be able to drive switching arcs at up to 600 ms^{-1} in air. The efficacy of magnetic arc driving has been demonstrated for reducing electrode erosion while at the same time increasing switching performance.

Both of these technologies unlock further possibilities in terms of switching cases and applications of disconnectors in future MTdc substations and grids.

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