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ROTATING CONSTRICTED SWITCHING ARCS BURNING IN GAS AND IN VACUUM

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Abstract. The method of controlling high-current switching arcs by transverse magnetic fields (TMF) forcing the constricted arc to rotate in a contact system is being applied successfully to improve the breaking capability of vacuum interrupters and gas circuit breakers. We describe the behavior of magnetically driven switching arcs in vacuum and in gas environment. We report on experiments using high-velocity videography, magnetic probes, and spectroscopy; they deliver the velocity, the temperature and the voltage of an arc. We present models and simulations of the moving constricted arc burning in metal vapor and in air. And we describe a particular switching application of TMF arc control and explain a scaling law of the contact size with the current interruption capability.

Keywords: constricted arc, vacuum arc, gas arc.

1. Introduction

The method of controlling high-current switching arcs by transverse magnetic fields (TMF) forcing the constricted arc to rotate in a contact system is being applied successfully in the development of vacuum interrupters and gas circuit breakers. Rotating arcs distribute the energetic stress of the arc over the contact surfaces and to prevent overheating of the contacts and, in case of gas arcs, the gas environment. The track and the velocity of the arc strongly influence the switching capacity of the contact system. Detailed optical and magnetic experiments in combination with physical modeling and numerical simulation of the arc provide a profound understanding of the functionality of contact systems with superimposed TMF and thus allow a purposeful improvement of the performance of vacuum and gas switches up to high short-circuit currents.

2. Experiments

2.1. Concept of Arc Control by Tranverse Magnetic Fields

Without any technique of arc control, a switching arc constricts at high currents. The resulting arc diameter is determined by the balance of magnetic force and internal pressure gradient (pinch). The constricted arc is either immobile or, due to existing current loops, moves to the edge of the contact system, where it remains fixed. In both cases, the contact surfaces and an existing gas environment are overheated locally. Local overheating can be prevented by forcing the constricted arc to move across the contacts by applying a Lorentz magnetic force on the arc current.

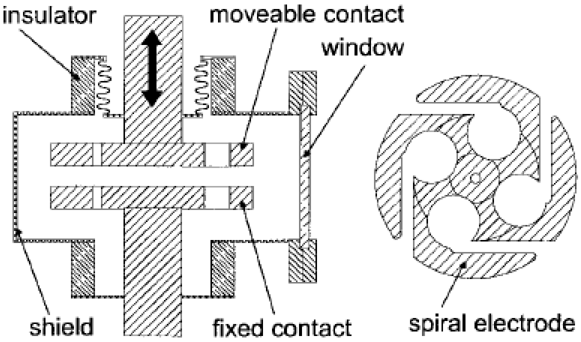

Figure 1. Conventional spiral-type TMF vacuum interrupter contact system.

2.2. Investigation of Vacuum Arcs

We studied experimentally cup-shaped and spiral-type "transversal magnetic field" (TMF) vacuum interrupter contacts with different diameters and arc currents. Fig. 1 (taken from [1]) shows a conventional spiral contact. The constricted metal vapor arc is drawn by separating a pair of 75 mm diameter copper-chromium (CuCr) electrodes to a gap of 8 mm at a velocity of typically 1 m/s. The arc is driven outward and rotates along the spiral arms by the Lorentz magnetic force.

The experiments were performed in a synthetic test circuit using a capacitor bank to generate 50 Hz sine half-cycles of up to 120 kA peak amplitude.

Arc position and arc velocity were measured by side-on observation of the rotating arc with a high-speed movie camera. For this purpose, the sealed-off vacuum tube was equipped with a viewing port window. Details are described in [1]. Simultaneous measurements with a set of several magnetic field probes provided independent information on the arc velocity movement. The arc velocity was recomputed from the modulation of the probe signal reflecting the times when the arc passes the probes.

2.3. Investigation of Gas Arcs

In case of gas arcs, the movement of the arc and the effect of external magnetic fields are important factors influencing switch gears. These features are some of the main reasons to simulate the switching arc to get a better knowledge to improve the geometry of the contact system. We developed a method of arc simulation for medium voltage switch gears, for example switches using "Rotating Arc" contact designs with permanent magnets. To validate the simulation, experiments were done in atmospheric air with a simple linear system of a stationary and a moving copper contact. The maximum contact gap was 22 mm, the experiments have been done with a current of 150 A and 500 A at 50 Hz, respectively. The arc position was measured by high-speed movie cameras. We used two cameras to get an approximate 3D position (one at the front side, one at the top side) of the arc. Simultaneous emission spectroscopy with side-on optical access to the arc provides information on the plasma temperature by fitting Boltzmann-plots to suitable spectral lines of the nitrogen gas species. This allows the validation of the simulated electrical arc conductivity. The third information gained in the experiment was the arc voltage. As boundary condition for the simulation, the movement of the contact and also the r.m.s. current of the experiment were measured.

3. Arc Modeling and Simulation

A moving arc that is not gradually accelerated requires a well-defined balance of driving and "frictional" forces acting on the arc. The arc experiences a permanent loss of momentum (restraining ("friction") force) that is balanced by the permanent acceleration of the plasma ions due to the Lorentz magnetic force (driving force). The computation of the arc velocity requires the solution of the complete mass, momentum, and energy balance of the arc in combination with all driving and frictional forces.

3.1. Analytical Vacuum Arc Models

We used different analytical models [1–3] to interpret the movement of constricted vacuum arcs and deliver expressions for the arc velocity.

The model published in [1] assumes a fixed surface temperature and a fixed total energy flux at the contact surfaces. The assumptions are justified insofar as the evaporation of contact material, necessary for the existence of metal vapor vacuum arcs, is insufficient below the boiling point. Most of the heat into the contact is used for evaporation.

An extended model developed in [3] is based on the energy balance equation similar to the model found in [1], but supplemented by an additional term that considers the momentum loss caused by the loss of neutral vapor leaving continually the arc column by diffusion. It explicitly takes into account the thermal response of the electrodes, assuming a variable surface temperature and a self-consistent heat transport. In particular, evaporation from the contacts and the corresponding cooling is treated quantitatively, using empirical relations from arc voltage and root diameter measurements at anode and cathode. The model [3] results in an explicit equation for the arc velocity,

$$v_A = \frac{\text{const.}\ I^{\frac{23}{16}}\ b_r\ h\ (c\ T_M\ +\ H_M\ +\ H_B)}{\alpha\ U\ I^{\frac{7}{16}}\ -\ \text{const.}'\ (\gamma\ T_M\ -\ T_0)\ \sqrt{v_A}}, \quad (1)$$

v_A = arc velocity, I = current, b_r = specific transversal magnetic flux density, h = contact distance, U = arc voltage, T_M and T_0 = surface temperatures of arc root (T_M) and before arc attachment (T_0), c, H_M, H_B = specific heat, melting and boiling enthalpy of contact material, γ = numerical sensitivity parameter, α = fraction of arc power dissipated to contacts.

3.2. Numerical Vacuum Arc Simulation

In principle, the simulation of a rotating constricted TMF arc has to be solved three-dimensionally (3D) because of the lack of symmetry of relevant contact geometries. Because of the high spatial gradients of the arc variables occurring in the intermediate zones towards electrodes, we chose in a first step a planar 2D simulation using the COMSOL Multiphysics platform.

In the model, the usual two circular contacts are replaced by two parallel straight electrode rails separated by a gap distance. The plasma column is described by a fluid dynamic approach with temperatures for heavy species and electrons. The energy loss by radiation is taken into account by a net emission coefficient. Two attachment zones at cathode and anode act as sheaths that describe energy and mass transfer between plasma column and electrodes. The electrodes are treated as current and heat conducting boundary zones. The TMF is superimposed as background field. The approach is similar to that treated in [4]. We applied the 2D model of the arc moving in the linear rail configuration to a realistic arc plasma that rotates in a circular cup-shaped TMF contact system and returns to the same location several times. For this purpose, the length of the rails was chosen to be equal to the circumference of the circular contact. After each arc transfer across the segment, the arc location is set back to the beginning of the segment, and the plasma and electrode parameters are stored to provide the initial conditions for the next arc transfer. The segment is allowed to cool until the arc returns and transfers additional energy to the electrodes. For test purposes, a gas arc model (SF_6 , ambient pressure = several bars) and a vacuum arc model with simplified electrode boundary conditions were implemented. The simulations were run for currents of several 10 kA, specific TMF amplitudes on the order of 1 T, and an electrode gap of 15 mm.

3.3. Gas Arc Simulation

Also in this case, the simulation of the switching arc has to be done by 3D. Because of the symmetry of the simulation model and the movies of the experiment, it was decided to do the simulation in a 1/4-model with symmetry conditions. The simulation (CFD and electromagnetic) was done in Ansys CFX in combination with the MHD-module. During the opening of the contacts, a switching arc appears between the fixed and the moving copper electrode. The plasma is described by a fluid dynamic approach with temperatures for heavy species and electrons. The radiation is considered by the net emission coefficient. The anode and cathode are included by well known formulations. The simulation involves moving meshes. After a mesh criterion was reached, the simulation was stopped, a new mesh was loaded, and the results were interpolated on the new mesh. After the interpolation, the simulation restarted with the time code of the previous step. This includes also the position and current of the simulation at the last time step. The recorded current of about 150 A and 500 A (rated current) was simulated for a time period of 10 ms. After this time the gap between the electrodes reached 18 mm.

4. Results and Discussion

In this paper, we present particular examples of experimental and theoretical results.

Fig. 2 illustrates the simulated spatial structure of an arc plasma burning in atmospheric air environment and moving between two electrode rails separated by 15 mm. The distributions of arc velocity, current density, and temperature within the arc column 1 ms after arc ignition are plotted for a current of 10 kA and a TMF of 1 T. Pressures of several tens of bars are deduced from the simulation. Due to the action of the TMF, the flow of plasma is bended to the direction of arc propagation, and plasma velocities of the order of 250 m/s are approached in the mid-plane of the gap. When the gap distance is increased, the deviation from a straight column becomes more pronounced.

Fig. 3 shows a comparison of experimental and theoretical propagation velocities of the TMF vacuum arc as a function of the current. The results based on the model of [3] are obtained in a numerical computation. The iteratively calculated values of v_A correlate quite well with the data reduced from experimental tracks. The arc velocity increases almost linearly with the current amplitude and attains values of more than 300 m/s for currents of 120 kA. The results can be used to describe the number of rotations of the arc on a TMF contact and to explain the scaling law of the contact diameter with the current.

Fig. 4 documents a particular scaling law for the current interruption capability of a short-gap spiral-type TMF contact design used in low-voltage high-current vacuum circuit breakers. The figure shows the dependence of the breaking current of the contacts on their diameter. The results of synthetic tests and of computations based on the model of [3] are in good agreement. The capability linearly increases as function of the contact diameter. This finding can be motivated as follows: The temperature of the contact surface, besides the residence time of the metal vapor in the inter-electrode gap, impacts the performance of the contact. The temperature is determined by the time for one arc circulation on the contact and by the heating time at a fixed arc location. The cooling time, which is given by the ratio of the circumference of the arc rotation and the arc velocity, stays constant if the current varies linearly with the contact diameter. An almost linear behavior is expected and is indeed confirmed by experiment.

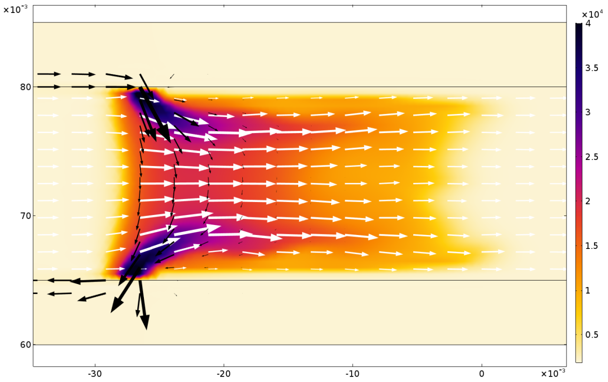

Figure 2. Simulated distribution of arc velocity (white arrows), current density (black arrows), and temperature (colors, legend in K) within a gas arc plasma moving between two electrode rails. Details see text.

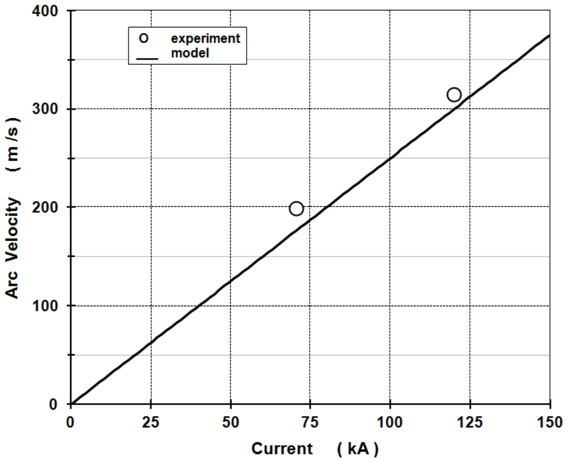

Figure 3. Comparison of experimental and theoretical propagation velocities of TMF vacuum arc as a function of current. Line: Model of [3]. Circles: measured values for CuCr contacts.

Fig. 5 compares the measured total voltage (including fall voltages) and the computed column voltage of the arc burning in atmospheric air. Experimental and simulated temporal evolutions are in satisfying

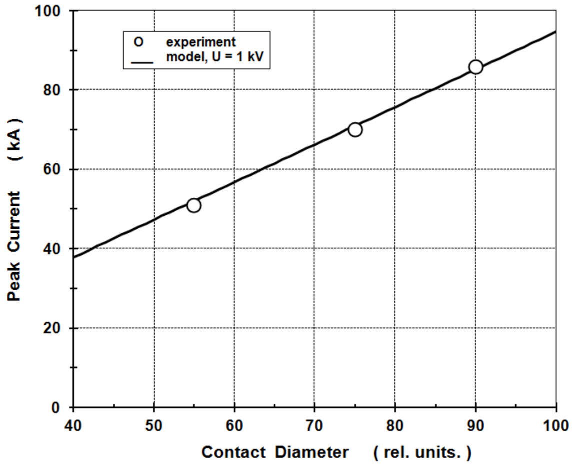

Figure 4. Experimental and theoretical short-circuit current interruption capability of TMF vacuum contacts as a function of contact diameter for the voltage level $U = 1\,kV$. Line: Model of [3]. Circles: measured values for CuCr contacts.

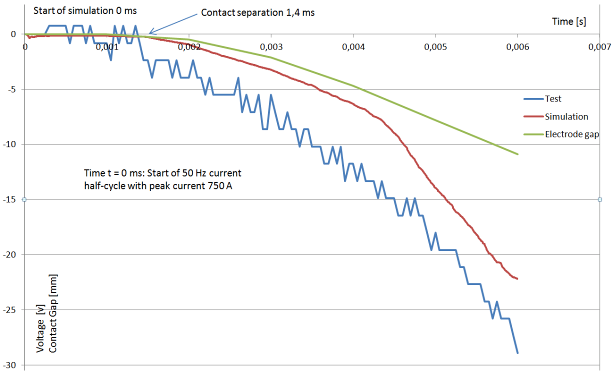

Figure 5. Experimental (blue) and simulated (red) arc voltages of gas arc vs. time. Measured contact gap (green) is input quantity for simulation.

agreement taking into account the measured voltage step at contact separation.

Spiral-type electrodes similar to the vacuum contact described in Fig. 1 were used in [1] for experiments with arcs burning in a low-pressure gas fillings (p = several tens of Pa), such as He, Ne, Ar, H_2, or D_2. The results documented that low-pressure gas arcs propagate in a pseudo-diffuse mode, do not need the metal vapor emission from hot electrode surfaces, and thus are able to propagate without the need of concentrated arc roots. The arcs achieved velocities far exceeding 10 km/s for currents of up to 25 kA. Low-pressure gas arcs move significantly faster than expected for atmospheric-pressure gas arcs and determined for vacuum arcs that move with velocities below 1 km/s.

5. Conclusion

The investigations presented here have been proven to be suitable to determine the velocity of rotating constricted TMF vacuum arcs and thus to predict the switching capability of TMF vacuum interrupter contacts. The applied experimental techniques are mature; more detailed results could be obtained by stereoscopic high-speed videography and tomographic 2D reconstruction of magnetic probe measurements. Though the analytical models describe the arc movement explicitly, relevant model parameters still have to be derived from experiments. The feasibility of a self-consistent planar 2D simulation of the TMF controlled arc moving in a linear electrode rail configuration has been demonstrated. A 2D simulation is suitable to describe the arc motion in a ring-shaped TMF contact and even the jumping over slits occurring in spiral-type TMF electrodes, as has been reported by [4]. Nevertheless, a quantitative optimization of real TMF contacts requires a full 3D treatment. The computational effort necessary to generate results from such simulations remains high; this has been shown by [5] who applied a 3D model to a rail-type electrode configuration.

The investigations show good results for switching arc simulation with the fluid air. Next steps are the simulation of SF_6 arcs and spectroscopic measurements with a high speed camera for transient thermal profiles. Also 3D modeling has to be performed to simulate the effects of external magnetic fields on the switching arc. Furthermore, there will be a change from linear moving contacts to rotatory moving contacts. Application of the 3D method to rotary contacts will deliver more detailed information and a better understanding of physical effects during the switching process, thus enabling a faster development of switch gears in medium voltage systems.

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