Investigations on Arc Rotation in Vacuum Circuit Breakers by External Magnetic Field Sensors

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Abstract: Over the last 30 years vacuum circuit breakers have become the dominant switching device in the medium voltage level. Vacuum has also become increasingly important for switching in high voltage applications. The greatest challenge a circuit breaker has to meet is the breaking of short circuit currents, which can reach up to 72 kA at the medium voltage level. Therefore, a matter of particular interest is how many short circuit currents the circuit breaker can safely interrupt. With extremely used contacts the arc will not rotate any more, and the breaking capability is drastically reduced. This research project focuses on developing a measurement system that is able to detect the arc movement characteristics of an RMF (radial magnetic field) contact system. The arc movement is measured by analysing the magnetic field signals of several external induction coils modulated by the rotating arc. This permits the analysis of the dynamical characteristics of constricted vacuum arcs rotating in a commercial vacuum circuit breaker. The benefit of this approach is that commercially available vacuum bottles can be used, without any special preparation. The working principle of this measurement system is discussed as well as the additional effects, which have to be taken into account in order to correctly analyse and interpret the measured signals.

1 INTRODUCTION

At the moment of contact separation during short current interruption the last conducting area of the contact surface heats up immensely. As a result some material of the contact surface will vaporize. The current to be interrupted ignites a diffuse metal vapour arc. At a current of 10 kA and above the so far diffuse arc will be constricted by its own magnetic field.

The constricted arc causes a more intense overheating of a smaller area on the contact surface than the diffuse arc does. There are two strategies to prevent heavy erosion effects due to the melted and re-solidified metal.

Axial Magnetic Field (AMF) contacts intend keeping the arc diffuse in order to distribute erosion uniformly over the whole contact surface.

The special shape of Radial Magnetic Field (RMF) contacts causes a strong radially oriented magnetic field in the contact gap. As a result an azimuthally oriented Lorentz force is generated, which accelerates the arc in a rotary motion. This contact geometry aims to distribute the erosion over a circular area at the outer regions of the contact surface.

There are two main types of RMF contact geometries. Cup shaped RMF contacts provide a ring shaped surface on which the arc can move along. Spiral shaped RMF contacts consist of a Copper Chromium (CuCr) alloy, which is sliced into a spiral shape. The current to be interrupted flows through the spiral arms and feeds the arc from behind. The magnetic field caused by this current path is radially oriented at the contact gap.

After a few short circuit switching processes the spiral arms begin to change their form cause of erosion effects. The melted and re-solidified contact material fills the gap gradually between the individual spiral arms. Eventually this gap will become bypassed by an electrically conducting bridge of contact material, and the current is able to flow through more than only one spiral arm. This causes a substantial decrease of the radially oriented magnetic field. As a result, motion of the constricted arc will slow down enormously. The resulting increase in vapour generation leads to additional slowdown of the arc, and the local overheating causes pronounced afterglow.

Therefore, it is important to investigate the movement behaviour of the arc during the switching process. To date, this is mainly done by special optical measurement systems, e.g. high-speed cameras. Optical methods require special experimental setups, such as vacuum bottles with glass instead of ceramic housings or special model vacuum chambers with observation windows. It is also not possible to use a vapour shield, at least it has to be manipulated in order to provide openings for taking videos. Therefore, most test setups differ from bottles from the stock in their dielectric behaviour.

This contribution reports about a measuring system designed to observe the arc rotation in a commercial standard vacuum circuit breaker. It also discusses results and findings of erosion effects as well as some effects, which have to be taken into account in order to correctly interpret the measured values.

2 MEASURING PRINCIPLE

Four air coils are arranged around the test bottle at 90° intervals and at the same level as the contact gap. This is shown in **Figure 1** and **Figure 2**. The current, which flows through the arc, causes a magnetic field. When the arc starts rotating, the origin of the magnetic field will also start moving. A tangentially oriented change of the magnetic flux at the position of the four coils induces voltages that can be measured.

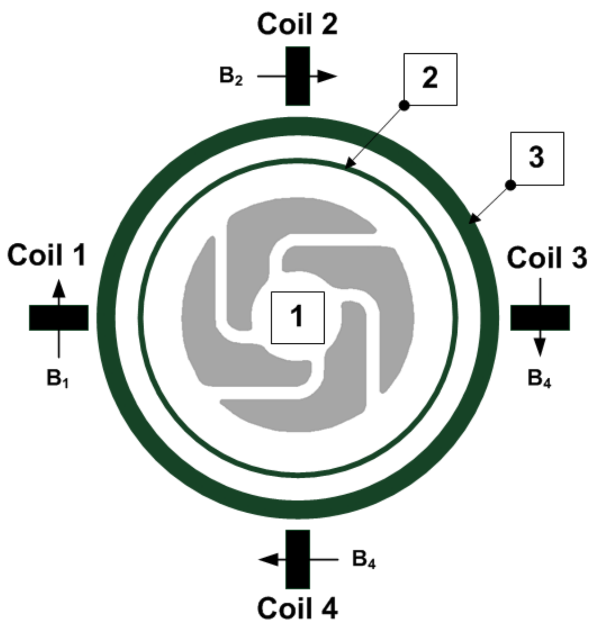

Figure 1: Arrangement of the four sensor coils along the outside perimeter of the ceramic housing (cross sectional top view) 1) spiral contact surface 2) vapour shield 3) ceramic housing

In order to evaluate the arc position two differential voltages are calculated. This is done by subtracting the opposing coil voltages from each other. Each of the two differential voltages contains the position information for one axis of a two-dimensional Cartesian coordinate system that represents the contact surface. A constricted arc moving close to the centre of the contact surface will induce nearly the same voltage in each of the four coils. As a result the two differential voltage signals will be nearly zero. This will lead to a position in the two-dimensional Cartesian coordinate system close to the origin.

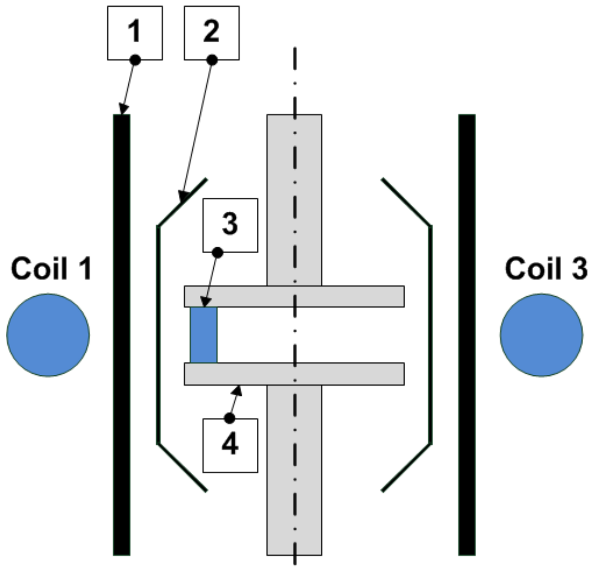

Figure 2: Idealized cross sectional side view of a bottle with burning arc 1) ceramic housing 2) vapour shield 3) arc 4) contact plate

While an arc will induce almost identical voltages in all four coils as it moves along the outside perimeter of the contact surface the voltages will appear time delayed to each other. When the arc passes one of the coils a profound change of the magnetic flux appears inside the coil, which results in a peak of the induced voltage. This is shown in **Figure 3**. The induced coil voltage allows a quick check if the attempt to create a rotating arc was successful or not. Additional facts are described in [1].

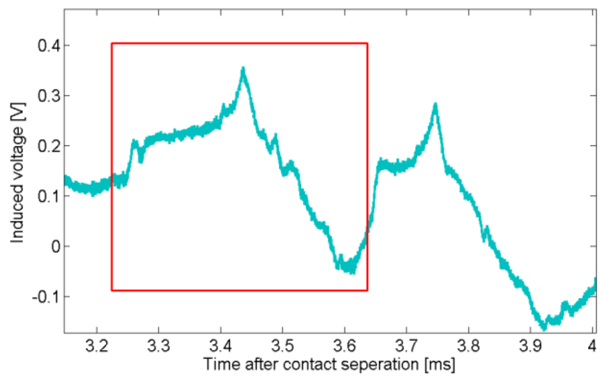

Figure 3: Induced voltage in one of the four sensor coils. Red window: induced voltage caused by half a rotation of the arc.

3 TEST SETUP

A plastic cuff carrying four sensor coils is fastened to the outside of a commercially available bottle at the level of the contact gap. It is not necessary to remove the bottle from the switchgear.

Each sensor coil is placed in a metal housing, which provides enhanced shielding against external electromagnetic noise. In addition, all electrical wiring is shielded against electromagnetic interferences. In order to receive a clear signal and to minimize interferences, the coils have to be positioned as close as possible to the ceramic body of the vacuum bottle. At the same time it has to be ensured that electrical insulation between the coils and the tube is sufficiently high. This is important because the vapor shield can take an electrical potential up to the maximum recovery voltage.

The recorded voltage values are measured by a data acquisition system that is connected to the test object, by using battery powered electric/optical converters and optical fibers. This approach eliminates any signal interference. In addition, it avoids all problems arising from potential differences. For further information about the test setup see [2].

4 DATA PROCESSING AND ANALYSIS

The measured voltages contain two different types of information. The main signal is the same for all coils. It is a 50 Hz cosine signal that originates from the sine half wave of the breaking current. These cosine signals have the same phase and shape at all four coils but they differ in amplitude. Reason for that are minute differences in the coil geometries. The coils are handmade and installed in metal enclosures. Therefore, it is important to test the coils before their first use and to find closely matching pairs. In order to compensate for the coil voltage differences, the four voltages are scaled such that their maxima have the same values. The next step is to subtract the opposing coil voltages from each other. This step eliminates the superimposed cosine signals. **Figure 4** shows the two differential voltage signals evaluated from the four individual measured coil voltages.

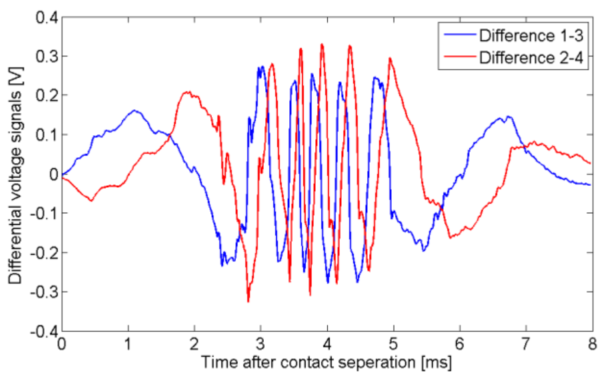

Figure 4: The two differential voltages which contain the position information for the two-dimensional Cartesian coordinate system

The other information contained in the coil voltages is the arc position. A single rotation of the arc can be identified by a peak appearing at specific time delays in each of the four coil voltages. This is illustrated in **Figure 5**. The time delay depends on the speed of the arc.

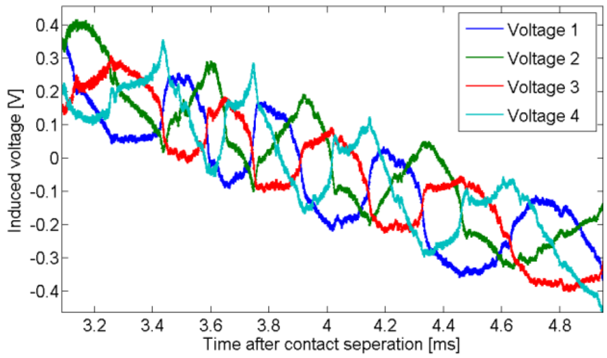

Figure 5: The four sensor coil voltages induced by four arc rotations

Assuming that the arc does not leave the contact surface it is then possible to establish a relationship between the voltage values and the positions on the contact surface. As a result it is possible to visualize the path of an arc along the contact surface during a single current breaking process. **Figure 6** illustrates such a process.

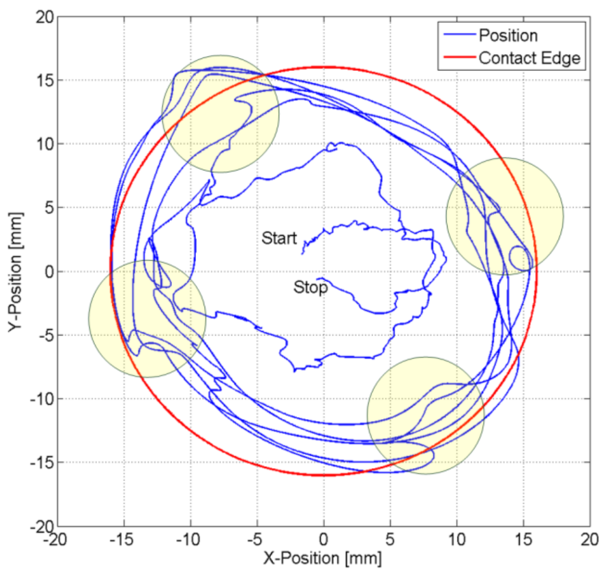

Figure 6: Plotted path of the arc on the contact surface during one current breaking process. Yellow circles: identified locations of the four spiral arm tips

It is apparent that the arc completed numerous rotations around the exterior perimeter of the contact system. According to the collected data the arc is located in the center of the contact plate immediately after the contact separation. These values are typical for a diffuse burning arc. Starting at a current of 10 kA and above the arc contracts, and after a short acceleration phase begins to rotate on the exterior perimeter of the contact surface. The arc decelerates slightly at the spiral arm tips because it has to jump over the gap from one spiral arm to the next. This process distracts the arc minimally from its uniform path, see **Figure 6**. It is reasonable to assume that these small changes in the path indicate the locations of the four spiral arm tips.

By applying the Pythagorean Theorem it is possible to calculate the spatial distance between two points of measurement. Since the sampling frequency is known it is possible to calculate the arc velocity. The velocity vs. time curve of the measurement of **Figure 6** is charted in **Figure 7**.

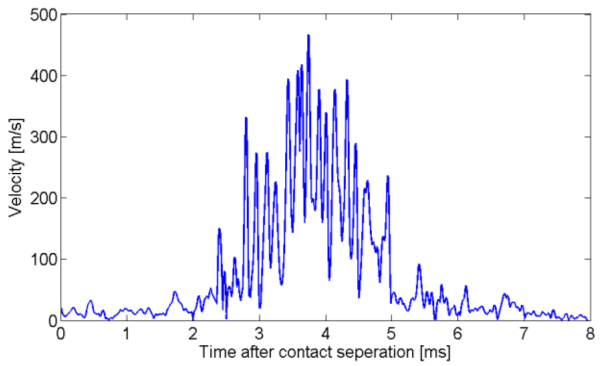

Figure 7: Arc velocity vs. time during one current breaking event

The moment of contact separation is characterized by a disturbance that results in unrealistically high measured sensor coil voltages. After about 2 ms the arc constricts and accelerates rapidly. When the current decreases the forces acting on the arc decrease as well. At the same time a counter reaction is generated by the momentarily increased contact separation, which in turn causes an increased force. However, this effect is not strong enough to entirely balance out the effect of the decreasing current. As a result, arc velocity is decreased and returns to its diffused state shortly before it reaches current zero. The maximum value for the arc velocity shown in **Figure 7** is slightly above 450 m/s. This unrealistically high value is caused by the non-uniform motion characteristic of the arc. It is possible that the arc performs a gradual movement. This will lead to a stepwise changing magnetic flux at the position of the sensor coils, which will be interpreted as unrealistically high arc velocity values.

When the positional data and the velocity data are charted together a velocity road map of each switching event can be generated. **Figure 8** gives an example for the case depicted before in **Figure 6** and **Figure 7**.

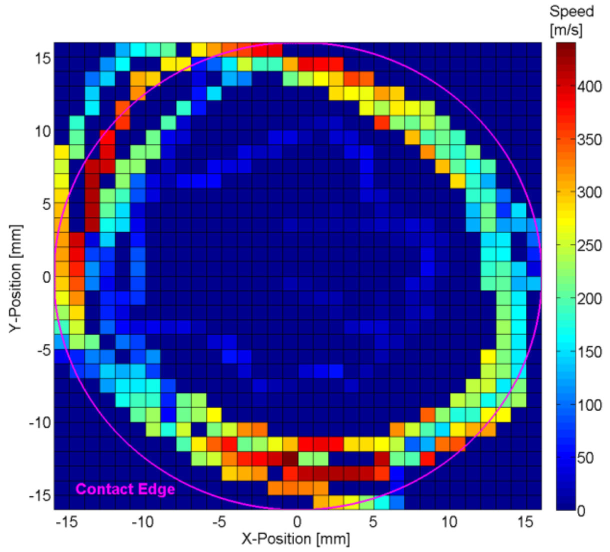

Figure 8: Velocity road map of the contact surface for one current breaking process

If all data points of all measurements of one bottle are charted together an arc travel characteristic of a contact system for the hole lifetime of a single bottle can be shown. An example is given in **Figure 9**.

The locations of the spiral arm tips can be identified by the low average velocity values in **Figure 8** and **Figure 9**.

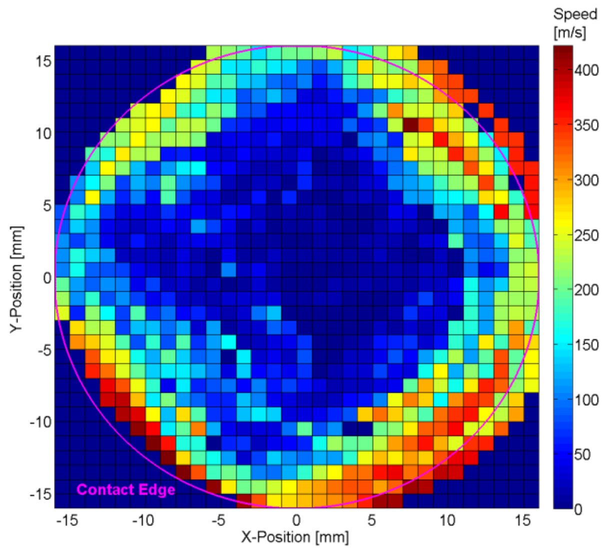

Figure 9: Velocity road map of the contact surface for five current breaking processes.

5 DETECTION OF EROSION EFFECTS

Melting of one spiral arm tip to another one results in a strong decrease of arc velocity. **Figure 10** illustrates a switching process where all four spiral arm tips were melted together with their neighboring spiral arm. Because of this erosion the contact system was not able to force the arc to more than one rotation. A moderate motion of the arc indicates the beginning of erosion even if the bottle was able to break the current successfully.

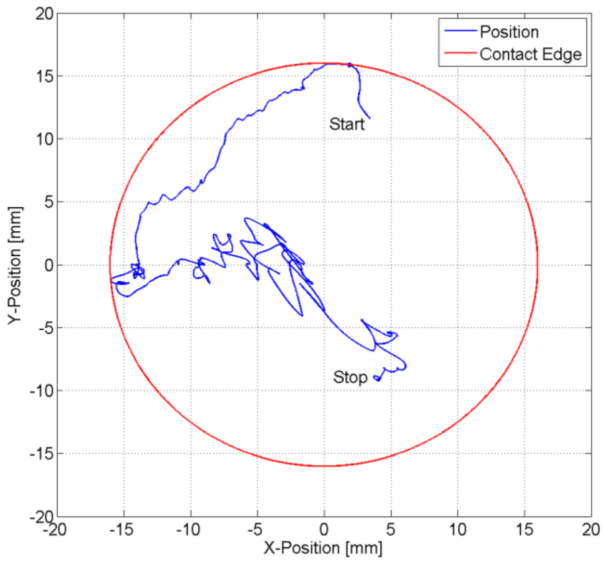

Figure 10: Plotted path of the arc on the contact surface during one current breaking event, where all four spiral arm tips are molten together with their neighboring spiral arm.

6 ADDITIONAL EFFECTS TO BE CONSIDERED

There are numerous additional effects that have to be taken into consideration in the determination of position and velocity but cannot be discussed here in detail. For instance, the voltage that is induced into the sensor coils, is directly proportional to the rate of change of the magnetic flux. The rate of change of the magnetic flux depends on the test current itself. Also small fluctuations are able to induce a non-negligible voltage. Furthermore, the small size of the entire setup has to be taken into consideration. It causes a notable dependence of the effective coil surface from the actual arc position.

The magnetic field around the arc (ideally assumed to be cylindrical) decreases proportional to 1/r from its origin. This proportionality results in a misrepresentation of an originally circular track to a rectangular shaped representation of the arc movement characteristic. This effect can be seen e.g. in **Figure 6**. This misrepresentation leads also to unrealistically high velocity values. In the future a compensatory method will be developed that retrospectively will correct the misrepresentation mathematically.

When the arc jumps from one position to another or if one arc extinguishes and another arc takes over the current, this will result in a big change of the magnetic flux at the position of the sensor coils. This will result in an unrealistically high measured apparent velocity. In addition, it effects the scaling of the coil voltages, which have to be applied to determine the relationship between measured voltages and position of the arc on the contact surface.

While the measuring system described in [1] relies on the same measuring principle it uses Hall-plate detectors instead of sensor coils. These sensors are considerably more sensitive to electromagnetic interferences. Therefore it is necessary to provide a massive shielding, which unfortunately also can influence the measuring results. The advantage of the Hall-plate detectors is that they do not report the rapid jumps of the magnetic flux at the position of the sensors as voltage peaks therefore avoiding the report of unrealistically high velocity values.

7 CONCLUSION

The presented results show that it is possible to investigate the motion characteristics of a constricted arc just by measuring the tangential magnetic field in the close vicinity to a vacuum circuit breaker bottle. The influence of the shape of a spiral contact system on arc motion can be detected and analyzed. It has been shown that the uniform movement of the arc at the spiral arm tips is disturbed. This leads to increased erosion at those locations on the contact surface. Elimination of the Hall-plate detectors, as used in [1], leads to a drastically decreased susceptibility to electric noise fields.

Advantage of this measuring method is the simple set-up, which allows for using unprepared, commercially available bottles for the investigations. This set-up also facilitates investigation of the influence of the original vapor shield and the original housing of the bottle on the switching behavior.

Future experimental and developmental work on this measuring system will focus on compensating for some of the above described effects that currently still to a certain degree distort the measuring results and have so far led to increased velocity values.

REFERENCES

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