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DETERMINATION OF THE MICROSCOPIC FIELD ENHANCEMENT FACTOR $\beta$
OF PRESTRESSED VACUUM INTERRUPTER CONTACTS

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Abstract - The microscopic field enhancement factor $\beta$ and the field emission area $a$ of variously prestressed vacuum interrupter contacts were investigated using the Fowler Nordheim equation. Additionally, the corresponding breakdown voltage values were considered. Statistically evaluated results are shown and discussed.

INTRODUCTION

The contact surface microstructure of a vacuum interrupter is strongly affected by the type and the preceding switching operation. This causes a badly defined dielectric withstand strength of the contact gap leading to an unreliable insulating behaviour of open vacuum interrupters. For this reason an investigation on a statistical basis was started recently in order to learn about the relevant phenomena influencing the breakdown performance of an open vacuum interrupter gap [1]. Variously prestressed contacts were tested by variously shaped voltage curves in all combinations. Beside an insight into the dielectric withstand behaviour of the gap the results also yielded conclusions about the surface microstructure and the initiating breakdown mechanisms.

In addition to this research the microscopic field enhancement factor $\beta$ and the emission area $a$ were determined after prestressing the contacts by various types of switching operations. The results are presented in this paper and yield more insight into the surface phenomena of a vacuum interrupter under actual conditions.

PROCEDURE

The tests were carried out with
- Rogowski profile shaped copper or tungsten electrodes in an experimental chamber at $10^{-8}$ torr (electrode diameter 40 mm, gap length 5 mm)
- a commercial vacuum interrupter valve (15.5 kV, 800 A, 12 kA); 5 mm gap length, Cu contacts

New contacts were conditioned by 100 dc arcs (100 A, 500 ms) in order to produce clean and well defined surfaces. Then the contacts were stressed by series of one of the following switching operations:
- no load close-open operation without arcing (NL)
- no load close-open operation after one conditioning dc arc of 100 A, 100 ms (NL/arc operation)
- no load closing followed by a 100 A dc opening arc of 100 ms or 1000 ms duration
- no load closing followed by 50 Hz, 5 kAms interruption (5 ms arc duration)

Fifteen seconds after each switching operation a voltage pulse was applied across the open gap rising to 20 kV or 0.1 kV/ms respectively. The 20 kV/ms pulses were increased until breakdown occurred whereas the maximum voltage of the 0.1 kV/ms pulses was limited by the supply to voltage values below the breakdown voltage.

During the tests the field emission current (FEC) $\leq 100$ nA was measured. The corresponding Fowler Nordheim (FN) curve was plotted by a computer which also calculated and detached the capacitive gap current. Finally the microscopic field enhancement factor $\beta$ and the field emission area $a$ were printed out.

RESULTS AND DISCUSSION

1. Determination of $\beta$ and $\alpha$ after various switching operations - Table 1 shows that the surface of both the valve contacts and the Cu contacts are influenced by the preceding switching operation in the same way. After no load close-open operations preceded by a 100 A dc arc (NL) the mean values $\bar{\beta}$ were highest connected with lowest mean breakdown voltages $V_B$. (All $\beta$ - and $\alpha$ values were calculated using the FN equation at an assumed work function of 4.6 eV.)

A 100 A, 100 ms dc arc decreases $\beta$ causing an increase of $V_B$. This effect is more significant, if the arc duration is extended to 1 sec. (as shown for Cu contacts). $\beta$ and $V_B$ values indicated surface smoothing by 5 kAms interruption arcs. Repeated no load switching (NL) decreased $\beta$ below the corresponding values for NL operation. All these tendencies concerning the breakdown voltages agree with [1].

The evaluation of the FEC immediately before breakdown (critical prebreakdown current $I_{cb}$) shows that $I_{cb}$ depends on both $\beta$ and $\alpha$. High $\beta$ values were connected with low values of both $\alpha$ and $I_{cb}$.

Table 1 also shows a more or less significant correlation between $V_B$ and $\beta$ manifested by a negative correlation factor $p(\beta, V_B)$. After 5 kAms interruption, however, $p(\beta, V_B)$ was positive for the Cu contacts indicating the superposition of an initiating mechanism which is not governed by the FE phenomenon. In this case the peak value of the arc current was close to the threshold of anode spot formation and increasing the likelihood of particle breakdown [1]. When 5 kA were interrupted by the valve the arc certainly was in a diffuse mode but...
according to [1] particle breakdown is likely too. This may explain the lower p value compared to that after the 100 A dc arc. Further evidence for this assumption is gained by the fact that in some cases the FN curves were exactly identical before and after breakdown, i.e. no main emission site was involved in breakdown excluding a FE initiated mechanism. Nevertheless the fact that the critical microscopic field \( E_C = \phi / \varepsilon \) was nearly constant for all switching operations and independent of the \( \varepsilon \) value indicates that breakdown mainly is initiated by FE at a constant mean FE current density \( J \).

Comparable measurements with tungsten contacts yielded \( \varepsilon \) values one order of magnitude less than for Cu electrodes. In this case the prebreakdown current curve showed significant microdischarge pulses which caused breakdown before the FEC reached a critical value.

2. Changes of \( \varepsilon, \alpha \) due to the applied voltage - If a series of five consecutive voltage pulses (0.1 kV/m) were applied in intervals of 4 min. (without any breakdown) \( \varepsilon \) was decreased especially after no load switching (NLC). Fig. 1 shows the mean values \( \varepsilon \) and \( \alpha \) of six test series across the pulse number. Each pulse was switched off when the FEC increased to 1 mA. The corresponding FN curves started as straight lines at low currents and were bended toward lower current values at higher voltages indicating a general decrease of \( \varepsilon \) during the test. Also unsteady fluctuations were superimposed especially at higher FEC values showing a general instability of the emission sites.

After at least four pulses the \( \varepsilon \) values approached a saturation value which was nearly independent of the original value produced by the switching operation. DC voltage applied for 30 sec.

3. Influence of pressure on \( \varepsilon \) and \( \alpha \) - If the pressure was increased to \( 10^{-5} \) torr with \( O_2 \) or \( N_2 \) the \( \varepsilon \) values decreased and \( \alpha \) values increased (Fig. 2). This effect was significant if the contacts were prestressed by a 100 A dc arc especially for oxygen. However, after no load operations (NLC) the influence of pressure was negligible.

Due to the specified test procedure not described in detail it is evident that the changes of \( \varepsilon, \alpha \) are caused by surface layer growth. The authors suppose that because of this surface layer the work function is increased yielding lower calculated \( \varepsilon \) values at \( 10^{-5} \) torr. It is not yet clear why this effect occurs only after arcing and not after no load switching, but it is assumed that the arc increases the surface layer growth in some way.

**CONCLUSIONS**

Vacuum interrupter Cu contacts show a clear correlation between the breakdown voltage and the microscopic field enhancement factor \( \varepsilon \). This indicates a mainly field emission governed breakdown mechanism. Nevertheless the probability of a particle breakdown increases after interruption of higher currents even for diffuse arcs.

The surface microstructure and the emission behavior depends strongly on the prestress of the contacts. Obviously the amount of charge transfer by the arc as well as the number of cathode spots influence the \( \varepsilon \) and \( \alpha \) values.

The extremely high \( \varepsilon \) values especially produced by no load switching call in question that the assumed work function of 4.6 eV is representative for interrupter contacts prestressed at actual conditions; particularly as the results for increased residual pressure gave the idea that the work function is influenced by the contact surface layer.

As already assumed in [1], consideration of the critical field emission current yields a rough qualitative insight into the surface microstructure of the interrupter contacts; especially when switching low currents or performing no load operations.

The breakdown voltage of a vacuum interrupter gap is strongly influenced by the history of the contacts as well as by the applied testing voltage itself. Measurements without considering those facts can yield results which are not representative for the insulating performance the breaker would have under actual conditions [3].

The occurrence of microdischarges for tungsten electrodes not observed for Cu contacts indicates that the results obtained hitherto may not be generally valid for other materials. Further investigation is necessary in order to reveal this matter.

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