Pressure Estimation in Vacuum Circuit Breakers

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ABSTRACT

The pressure of vacuum switching elements after production is checked normally by Penning or magnetron methods (combined electrical and magnetic field). Vacuum in the range of \(10^{-1}\) to \(10^{-4}\) Pa can be measured in this way. After assembly into circuit breakers however, these methods are not applicable. \(f\) interruption performance during the make operation was proposed earlier as a possible alternative. Further investigations show that differences in the number of \(f\) prestrike current loops can be found in the pressure range of \(10^{-1}\) to \(10^{5}\) Pa. Current chopping of dc arcs between 5 and 30 A during opening operation may be another option for determination of the pressure range by measuring the lifetime of the arc, but the resolution in the vacuum range < \(10^{-1}\) Pa is too poor.

1. INTRODUCTION

VACUUM circuit breakers, load switches and contactors have been introduced in MV distribution and industrial applications during more than a quarter of a century. The experiences are very good and there has not been a need to check the vacuum pressure. The manufacturers have improved the vacuum soldering techniques and the choice of material to such a level of quality that long lifetimes are guaranteed.

Production tests after assembly are made in the factory by Penning or magnetron methods. Voltages to 5 kV and magnetic fields to 0.1 T are applied simultaneously. The ion current between contacts or between contacts and screen is a measure for the vacuum quality but the value is design dependent. After a period of storage by the manufacturer the tests are repeated and vacuum tubes with increased ion currents are rejected. These methods are not useful for utilities because the vacuum tubes have to be disassembled from the switchgear with all the risks of improper remounting. Although the lifetime of modern vacuum tubes is estimated as more than twenty years, failures of early interrupters cannot be excluded completely. For industrial application after a large number of operations, leakage may occur by fatigue of the metal bellows. But also in distribution applications with a negligible number of operations, the vacuum quality may be reduced by long term diffusion, intercrystalline corrosion or deactivation of the getter material. Hence it would be very practical to have on site test methods for vacuum interrupters of earlier production years.

2. DIELECTRIC TESTS

Most utilities have ac and dc test equipment for test voltages of 30 to 50 kV. Hence it is quite evident that these methods have been used also for tests on vacuum switchgear. Unfortunately the voltage withstand in vacuum is already at maximum at \(< 1\) Pa. Tubes with a vacuum from 1 to \(10^{5}\) Pa (atmospheric pressure) can be
selected by applying a test voltage. In case the tubes are mounted in SF₆ (GIS) they will be filled with SF₆ and the voltage withstand is high and insufficient differences between good and bad tubes will be found.

There also exists commercial test equipment for good-bad selection of vacuum tubes using an ac or dc supply, with the same limitations. We have tried to improve the sensitivity of the ac method by measuring the dc component of the emission current from the low voltage contact. This work was a continuation of earlier work on Fowler-Nordheim measurements [1]. In an experimental tube on a pumped system we found at a pressure 10⁻¹ Pa an emission current of 30 nA, decreasing to < 5 nA at 10⁻² Pa under an ac voltage of 25 kVrms.

At the same time the dc potential of the shield electrode of the vacuum tubes was measured by a 10 GΩ Brandenburg HVDC meter (20 kV range). A remarkable effect between 0.1 to 1 Pa, and shield potentials to 1 kV was found. The physical explanation of those effects needs further research. Tests on vacuum tubes of different manufacturers also have to be made. It is important that the structure of the switchgear is discharge free to the maximum test voltage, otherwise the results will be influenced by external discharges.

3. HIGH-FREQUENCY INTERRUPTION PERFORMANCE

The status of the vacuum in the tube can be determined in principle by interruption tests at suitable current levels. At network frequency and voltage this approach is less practical by the high kVA demand of the supply circuit. Proposals have been made to use the HF interrupting performance as an indicator for the pressure [2]. The advantages of this testing method is that relatively high $\frac{dI}{dt}$ and $\frac{dv}{dt}$ can be obtained by relatively compact capacitive storage. The frequency of the discharge current is given by the capacitance and inductance of the circuit, the steepness of the recovery voltage by an $RC$ network. Tests have been performed at high frequencies (250 kHz, 15 kV, 200 A) and medium frequencies (16 kHz, 25 kV, 800 A) during the make operation of the contact system. A typical oscillogram of such an operation is shown in Figure 1. The number of pre-ignition current loops (of the first re-ignition wave train) as well as the time between first re-ignition and contact touch (pre-ignition time) has been measured (Figure 2) at varying pressure. This time varies between 0.2 to 2 ms.

The sensitivity of the hf current interruption performance for changes in pressure was measured in two ways:

1. By evacuating a demountable laboratory interrupter in an oil-free vacuum system until 10⁻⁶ Pa (after bak-
ing out and arc conditioning) and allowing a controlled leak of air through a precision valve increasing the pressure 10 times every measuring sequence until 1 Pa;

2. By evacuation of a commercial interrupter with a diffusion and turbomolecular pump, and arc conditioning at the lowest possible pressure.

Both methods did not show a significant difference in interrupting performance with respect to hf current in the pressure range $10^{-5}$ to $10^{-1}$ Pa.

### 4. CABLE DISCHARGE TESTS

This method could be used in the field, where cables are connected to the circuit breakers. This configuration provides a natural way of producing high frequency discharges in the circuit breaker, the vacuum quality of which is to be checked, in the following manner. One of the cable cores is charged by a dc source of 15 to 30 kV. Thereafter the cable is discharged by a closing operation of the VCB. The discharge current waveform of a cable is more or less rectangular caused by the distributed parameters, with a peak current of $V/Z$. For 15 kV and $Z = 25\Omega$ a peak current of 600 A is made with a high $\frac{dI}{dt}$. The frequency of the discharge is determined by the length of the cable. We have made tests with cable lengths of 300 m in the laboratory and 2 km in the field (frequency 100 and 16 kHz). The pre-ignition time and the dc arc lifetime (Section 5) have been measured in three circuit breakers (installed over the last 13 years) with nine vacuum tubes (2 km cable). The results are shown in Figure 3. The statistical spread of the data points both for dc arc lifetime and pre-ignition time was in the order of 30%. From the results it may be concluded that the vacuum quality of the T-pole of the third circuit breaker may be suspected of loss of vacuum quality. The number of pre-ignition current loops was varying between 1 and 3, showing no evident correlation with the other measured quantities.

### 5. dc ARCING TESTS

The interrupting performance of low current dc arcs could have a relation to the pressure in the vacuum tube. This effect has been investigated with a dc supply ±300 V with a three phase rectifier from the 380 V low voltage network. The current is stabilized by series capacitors of 50, 100, 200 or 300 $\mu$F, giving currents of 5, 10, 20 or 30 A. An inductance of 30 mH is inserted in the dc path. The capacitance in parallel to the VCB is important for the value of the life time and the overvoltage generated after the current chopping. At high pressure (> 1 Pa) the arc will burn more or less permanently (> 30 s), when opening the contacts. At low pressure the lifetime of the arc varies between 0.1 and 10 s, depending on the current, capacitances parallel to the arc and the surface conditions of the contacts.

![Figure 3](image-url)

**Figure 3.**

dc arc lifetime (at 30 A arc current) and pre-ignition time for 9 vacuum tubes subjected to a 2 km cable discharge.

![Figure 4](image-url)

**Figure 4.**

Points: Average dc arc lifetime (commercial bottle 10.8 A, laboratory bottle 5.4 A). Dotted line indicates upper standard deviation.

For arc life time measurements, the degree of surface contamination probably has more influence than the back-
ground pressure in the bottle. For this reason, it is advis-
able to keep the arc lifetime sufficiently small, in order to 
avoid conditioning of the contacts by the measurement 

itself. An impression of the average dc arc lifetime, ob-
tained in the two experimental setups described in Sec-
tion 3 with its standard deviation can be obtained from 
Figure 4. As can be seen, no evidence of pressure depen-
dency in the interesting range $< 10^{-4}$ Pa can be gained 
from this measurements. This is in accordance with ear-
lier findings [4].

6. CONCLUSIONS

Vacuum state estimation by ac or dc test voltages

is only effective for pressures $> 2$ Pa. For pressures

$< 1$ Pa the test voltage can be withstood and sensitive

emission current measurements (1 to 100 nA) give some

indication if not superimposed by external discharges.

In the pressure range $10^2$ to $1$ Pa a shield potential

rise to $1.5$ kV has been observed during ac tests with

25 kV. The hf interruption ability of pre-ignition arcs

during a make operation gives a decreasing number of

current loops for lower pressure to $\approx 0.1$ Pa. Below $0.1$

Pa the number of loops has no significant relation with

the pressure.

Interuption of cable discharge currents with longer ca-

cables (1 to 3 km) gives a smaller number of loops than

short cables (100 to 300 m), probably due to the lower

d$\text{d}I/dt$. dc arc lifetime measurements with currents of 20

to 30 A have a tendency to give a shorter lifetime for

lower vacuum to $\approx 1$ Pa. For pressures $< 1$ Pa, arc life-
time does not seem a suitable indicator. For pressures

$> 1$ Pa the arc is not interrupted due to a rapid increase

in lifetime.

During field tests of cable discharges a correlation be-
tween pre-ignition time and dc arc time have been found,
suggesting a vacuum quality failure indicated by a signif-
ificant increase of both parameters. Further research for
the vacuum pressure dependence of these effects is nec-

essary.

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