The Comparison of Test Circuits with Arc Models

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Abstract - The arc-circuit interaction plays an important role in the current interrupting process of High-Voltage Circuit Breakers. For the development of circuit breakers, testing in the High Power Laboratory is necessary. For UHV circuit breakers new test circuits have to be developed. The design and development of new synthetic circuits relies on computer simulations only. A correct representation of the current zero behavior of the circuit breaker by means of an arc model is absolutely necessary. In this paper arc modelling, and the development of new test circuits are discussed and measurements of arc voltage and arc current are presented for two 72 kV SF₆ power circuit breakers.

Keywords:
circuit breaker, synthetic test circuits, transient recovery voltage, arc models, current zero.

INTRODUCTION

The interrupting power of circuit breakers has increased rapidly due to the use of SF₆ as extinguishing medium. The interrupting capability of a full pole single interrupting has surpassed the 10 GVA level. For development and acceptance tests, complete circuit breaker poles must be tested in the High Power Laboratory where the test conditions prescribed by IEC and ANSI standards are simulated [1,2].

The parallel current injection test method is an accepted way to test the thermal and dielectric interrupting interval of a circuit breaker in one test. But there is a principal limitation to the standard parallel current injection method and that is it cannot be used for the extreme power levels [3]. For breakers above 765 kV new test circuits have to be developed.

When an SF₆ circuit breaker interrupts a fault current, the whole process of current interruption takes place in a few microseconds. The rapidly changing arc conductance causes a strong arc-circuit interaction. For the design and development of new test circuits, computer simulations are the only possibility. In the computer simulations, the arc-circuit interaction must be represented by an arc model which resembles the behavior of an SF₆ circuit breaker in practice.

In this paper an arc model is described based on the decay of arc conductivity in the post-arc channel by recombination processes and electron attachment.

The arc parameters for the arc model are derived from the arc resistance. The results of arc voltage and arc current measurements are presented for two 72 kV SF₆ power circuit breakers.

THE ARC MODEL

During the current zero period the arc-resistance is of the same order of magnitude as the circuit impedance. This leads to strong arc-circuit interaction.

Before current zero the arc resistance is calculated with a Mayr-type differential equation for the arc conductance with a constant time parameter \( \tau \) and a current-dependent cooling power

\[
P(I) = p(P_o + C_1 I^{\gamma})
\]

in which \( p \) represents gas pressure and \( I \) the arc current. The non-linear arc resistance

\[
R_a = \frac{1}{G} = \frac{V}{I}
\]

is calculated from

\[
\frac{1}{G} \frac{dG}{dt} = \frac{1}{\tau} \left( \frac{1}{P(I)} - 1 \right)
\]

The three fitting parameters \( C_1, P_o \) and \( \tau \) are derived from the measured arc resistance \( R_a = 1/G \) and thus from arc voltage and current in the following way:

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- $C_1$ is derived from the arc voltage at currents in excess of 1 kA.
- $P_0$ is deduced from the slope in a plot of log($R_0(t_0)$) versus log($t_0$) in which $t_0$ is the time before current zero. This slope was found to be 1.2 - 1.3 for a rotating arc as well as a puffer-type SF$_6$ circuit breaker.
- $r$ can be derived from the log($R_0(t_0)$) - log($t_0$) plot for $t_0 < 5$ usec. A high extinction peak or sharp increase in $R_0$ for small $t_0$ means a small time parameter $r$. A time constant in the order of 1 usec leads to a resistance $R_0(0)$ in between 100 $\Omega$ and 1000 $\Omega$ at current zero.

After current zero the number density of charged particles (electrons, positive and negative ions) is calculated in the decaying hot gas channel, starting from an initial electron number density in accordance with $R_0(0)$ at current zero, as calculated with the modified Mayr model. The afterglow channel is assumed to be uniform with length $L$ and radius $r$. The conductivity of the channel changes due to changes in the electron number density $N_e$ caused by diffusion ($\gamma$), electron-ion recombination ($\beta_{ei}$), attachment ($\eta$) and ionization ($\alpha$). Also, the ion number densities $N_+$ and $N_-$ are changing with time; if charge neutrality is assumed then:

$$\frac{dN_+}{dt} = -\gamma N_e - \beta_{ei} N_+ N_e + \alpha_{eff} V_{dr} N_e$$

$$\frac{dN_-}{dt} = -\alpha_{min} |V_{dr}| N_e - \beta_{ei} N_+ N_e$$

$$N_+ = N_e + N_-$$

When a voltage is applied to this channel, the charged particles drift in an electric field $E=V/L$. Conductivity can be expressed as (see reference [4]):

$$G = C_e N_e \frac{T r^2}{p L} + C_i (N_+ + N_-) \frac{T r^2}{p L}$$

in which $T$ is the neutral gas temperature, $p$ the gas pressure and $C_e$ and $C_i$ constants depending on the gas (composition). Parameters like $\alpha_{eff} = \alpha - R$, $V_{dr}$, $\beta_{ei}$, $N_p = p/T$, $T$ and $r$ are all time-dependent and some are $E$-field or temperature dependent and will now be discussed in more detail.

The drift velocity $V_{dr}$ of electrons and ions in an electric field depends on the reduced electric field $E/N$, in which $N$ represents gas density. Linear dependence on $E/N$ is assumed. The proportionality constant is fitted to data from the literature in the region where $\alpha = R$.

The attachment coefficient in this region is only mildly dependent on $E/N$ and therefore taken constant. The ionization coefficient, however, increases strongly. The ionization coefficient $\alpha_{eff} = \alpha - R$ is defined as:

$$\alpha_{eff} = \max\left(\alpha_{min}, C_a \frac{V}{L} \frac{P(E/N)}{T} \right)$$

and shown in the diagram in fig. 1. For decomposed hot SF$_6$ gas the numerical value for $\eta$ is only about 1% of the value for cold SF$_6$ gas, because attachment is mainly to F atoms and in hot air it is about 0.1% of the value for cold SF$_6$ gas.

Recombination coefficients for molecular gases at room temperature are in the order of $10^{-14}$ m$^3$/s for ion-ion processes. In hot decomposed gases the temperature dependence has been taken into account by a factor proportional to $T^{-3}$; also numerical values were taken from measurements in air and SF$_6$ in the hot afterglow of a rotating arc experiment and have been normalized at 3000 Kelvin. The time dependence of the gas temperature $T$ is modeled as a double exponential decay, starting at 8000 Kelvin with time constants $\tau_1$ (10 usec) and $\tau_2$ (200 usec) of the arc layer. Finally, the arc radius $r$ is assumed to decay exponentially with a time constant $\tau$ (500 usec).

Arc conductivity and arc current can now be calculated in the afterglow as a function of the transient recovery voltage (TRV) generated by the
electrical network. A dielectric reignition in the hot channel is possible if the ionization coefficient $\alpha$ exceeds the attachment coefficient to cause an increase in electron number density $N_e$, outnumbering the e-i recombination and attachment. This happens when the TRV generates a reduced electric field $E/N$ exceeding $E/N_{\text{crit}}$. The increase in conductivity results in a high post arc current and finally a voltage collapse. The computation returns in this case to the Mayr model to calculate the fast and slow transients in the network properly. If the electron number density decay just after current zero is not fast enough (insufficient attachment and recombination), the post arc current will become high and so will the power input in the post arc channel. If this power input exceeds $P(0)$ by a certain factor (1.5), then the computation also returns to the Mayr model and the reignition is called thermal.

**THE ARC MODEL PARAMETERS**

The sensitivity of the conductivity of the post-arc channel to arc parameters, such as the electron-ion recombination coefficient and electron attachment coefficient, is described in reference [7].

Before current zero, a Mayr type equation with time constant parameter $\tau$ and current-dependent cooling power $P$ has been used. Therefore, three arc parameters must be known: a constant $C$ determining the arc voltage at high current, a minimum cooling power $P_0$ and a time constant $\tau$.

By a proper choice of $\tau$, $P_0$ and $C$ the arc voltage, extinction peak and conductance at current zero can be adjusted to measured values. The easiest way to obtain the three free parameters is to plot $\log G$ or $\log R$ versus $\log t$, where $t$ is the time before current zero. The constant $C$ is obtained from the arc voltage in the kA range of the current (where $U_b$ is nearly constant). Then from the slope of the curve between $t=50$ and $t=5$ microseconds $P_0$ can be deduced. Finally, $\tau$ is decisive for the shape of the voltage curve during the last microseconds before current zero, where an extinction peak in the arc voltage may occur depending on the values of $P_0$ and $\tau$ [5].

Two SF$_6$ power circuit breakers A and B were tested in a circuit shown schematically in fig. 2 at currents up to 21.2 kA$_{\text{r.m.s.}}$ and 31.6 kA$_{\text{r.m.s.}}$ respectively. The test circuit consists of a generator ($U_g$), TRV network ($R_i,C_i$) and an artificial line with damping ($R_d$). The arc current was measured at the supply side of the breaker under test by means of an inductive transducer of 0.1 $\mu$H, recording the $di/dt$ of this current. The arc voltage was measured with a capacitive voltage divider of 250 PF. Both signals were recorded with 10 MHz-12 Bit AD converters and stored in 4 kiloByte RAM. A time window of 400 microseconds around current zero was recorded during each test. The arc current and arc voltage for a successful interruption of 21.2 kA$_{\text{r.m.s.}}$ by circuit breaker B is shown in fig. 3 for the last 0.2 milliseconds before current zero and just after current zero when the TRV stresses the arc. An expansion around current zero of the arc current clearly shows the deformation of the arc current due to arc-circuit interaction and the small post-arc current (fig. 4). In fig. 5 the arc current around current zero for a reignition of breaker A is shown for 21.2 kA$_{\text{r.m.s.}}$. The arc resistance (fig. 6 and fig. 7) at current zero is below 100 $\Omega$ and does not increase fast enough to prevent thermal reignition. In the case of a successful interruption the resistance at current zero is already close to 1 k$\Omega$. 

![fig. 2](image)

*fig. 2* Test circuit used for the shortline fault tests

![fig. 3](image)

*fig. 3* Interruption of 21.2 kA$_{\text{r.m.s.}}$

**Circuit breaker B**

$U_{\text{arc}}$ $I_{\text{arc}}$

$U_{\text{arc}}$ $I_{\text{arc}}$

$U_{\text{arc}}$ $I_{\text{arc}}$

$U_{\text{arc}}$ $I_{\text{arc}}$

$U_{\text{arc}}$ $I_{\text{arc}}$

$U_{\text{arc}}$ $I_{\text{arc}}$

$U_{\text{arc}}$ $I_{\text{arc}}$

$U_{\text{arc}}$ $I_{\text{arc}}$
Interruption of 21.2 kA_{max}, expanded current trace of a successful interruption. Circuit breaker B.

Fig. 4

Interruption of 21.2 kA_{max}, expanded current trace of a reignition. Circuit breaker A.

Fig. 5

Measured arc resistance around current zero for a reignition. Interruption of 31.6 kA_{max}, Circuit breaker B.

Fig. 7

Measured arc resistance before current zero. Circuit breaker A.

Fig. 8

Measured arc resistance before current zero. Circuit breaker B.

Fig. 9

Arc parameters for the modified Mayr model can be found from the shape of the arc resistance curve, e.g. from a log-log plot of $R_{arc}$ versus the time before current zero as shown in fig. 8 and fig. 9. The values of $C$, $P_0$ and $\tau$ deduced for breaker A and breaker B are given in table I, together with the electron-ion recombination coefficient after current-zero.
<table>
<thead>
<tr>
<th>CB</th>
<th>C (V/bar)</th>
<th>P_c (kw/bar)</th>
<th>( \tau (\mu s) )</th>
<th>C_m (m^2/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>140</td>
<td>5</td>
<td>0.96</td>
<td>1.0 E-13</td>
</tr>
<tr>
<td>B</td>
<td>248</td>
<td>15</td>
<td>0.6</td>
<td>1.0 E-13</td>
</tr>
</tbody>
</table>

Table 1 Arc parameters for the modified Mayr Model and the electron-ion recombination coefficient

Circuit breaker B has a higher arc voltage (clear from the value C in table 1), a higher cooling power \( P_c \) and a shorter time constant \( \tau \) and can therefore build up a higher resistance for the same di/dt or peak current at the instant when the current and voltage pass through zero. After current zero the parameters for the recombination model can be derived from a comparison of the reignition behavior. In fig. 10 the calculated arc current in the interruption interval is shown. The calculated arc resistance as shown in fig. 11 closely matches the measured values.

CONCLUSIONS

The actual measurements were carried out on two SF_6 circuit breakers from different manufacturers. The circuit breakers were tested in a direct test circuit in KEMA's High Power Laboratory performing a short line fault test.

The measurements show a great difference in arc resistance when a breaker clears the short circuit current (1000 \( \Omega \)) or when it has a thermal reignition (100 \( \Omega \)).

For shorter arcing times the breakers have higher interruption capabilities.

The resistance of the arc channel of SF_6 puffer circuit breakers around current zero can be calculated very accurately with the KEMA arc model. Because of this accurate representation of the arc resistance, the KEMA arc model gives a good representation of the arc-circuit interaction of SF_6 circuit breakers and is a useful tool in the development of new test circuits.

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REFERENCES

[1] IEC-56 and IEC-427


Lou van der Sluis was born in Geervliet, the Netherlands on July 10, 1950. He obtained his M.Sc. degree in electrical engineering from the Delft University of Technology in 1974. He joined KEMA's High-Power Laboratory as a test engineer in 1977. He was involved in the development of a data acquisition system for the High-Power Laboratory, computer calculations of test circuits, design of test circuits and analysis of test data by digital computer. In 1990 he became a part-time professor in the Power Systems Department at the Delft University of Technology. In 1992 he became a full-time professor and chairman of the Power Systems Laboratory and High-Voltage Laboratory. Professor Van der Sluis is a senior member of IEEE and convenor of CIGRE WG 13-07 for the study of transient recovery voltages in medium-voltage distribution and high-voltage transmission networks.

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