THE INFLUENCE OF THE ARC VOLTAGE IN SYNTHETIC TEST CIRCUITS

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Abstract - **In this paper different arc voltage waveforms and KEMA arc models are used to study the stress of the direct SLF (short line fault) test circuit and the synthetic SLF test circuit on the TB (test breaker). For the synthetic test circuit the total arc energy input in the TB is less than in the direct test circuit, but just before the current zero the dI / dt and subsequently the arc energy input in the TB is higher. It is demonstrated that the arc-circuit interaction plays an important role for the TB to clear the fault. For SF_6 breakers with an arc voltage with a significant extinguishing peak, the voltage injection synthetic test circuit produces an overstress for the TB.**

Keywords:
circuit breaker, short circuit testing, synthetic test circuit arc voltage, arc-circuit interaction

INTRODUCTION

At the present time a complete pole of an SF_6 circuit breaker can consist of a single interrupting chamber with an interrupting power above the 10 GVA level. Even KEMA's High Power Laboratory, the largest test facility in the world, with a maximum short-circuit power of 8400 MVA and 145 kV - 31.5 kA three phase direct test capability, cannot verify the short circuit interrupting capability by direct test methods, and synthetic test circuits have to be used instead. [1]

Two types of synthetic test circuits, based on the injection method of a high-voltage circuit, are presently in use: the parallel current injection circuit and the series voltage injection circuit. In both methods the short circuit current is supplied from short-circuit generators or from the grid. For both the parallel current injection circuit and the series voltage injection circuit an AB (auxiliary breaker) is necessary to separate the current source and the voltage source. The insertion of the AB in a synthetic test circuit introduces an extra arc voltage in the test circuit and makes the arc-circuit interaction of the TB different from the interaction in the direct test circuit.

For the parallel current injection and the series voltage injection synthetic test circuits, the insertion of the AB gives the same influence on the TB in the high current interval. In the interaction period around current zero, however, the influence is different.

Because of the various interrupter designs, breakers of different manufacturers can have different arc voltage waveforms. During the current zero period the arc resistance of SF_6 breakers is of the same order of magnitude as the circuit impedance. Different arc voltage waveforms, especially the shape of the arc voltage just before current zero, will result in different arc-circuit interaction and this can result in different stress on the breakers, even if the test circuits have the same ideal (inherent) short circuit current and recovery voltage.

The waveform of the arc voltage just before current zero can be described by an arc model [2], and in this paper we use this arc model to study the arc-circuit interaction.

For a better understanding of the arc-circuit interaction, practical test circuits used by KEMA for SLF tests (85% short line factor) are used. The breaker is a puffer-type SF_6 breaker with a short circuit rating of 245 kV / 63 kA / 50 Hz. Figure 1 shows the series voltage injection synthetic SLF test circuit and figure 2 shows the parallel current injection synthetic SLF test circuit for full-pole tests. For the sake of comparison, a direct SLF test circuit (figure 3) was used. The parameters of this direct test circuit are dimensioned such that all the power is supplied from one source.

Because SF_6 breakers are sensitive in the thermal

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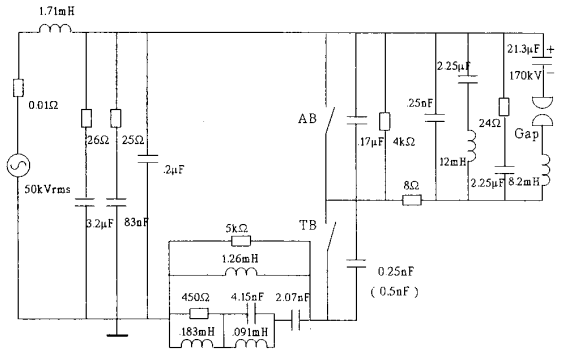


Figure 1
Voltage injection synthetic SLF test circuit

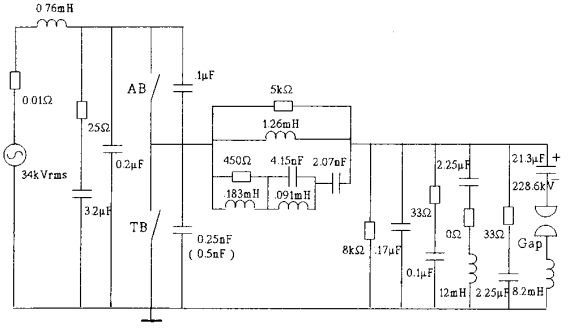


Figure 2
Current injection synthetic SLF test circuit

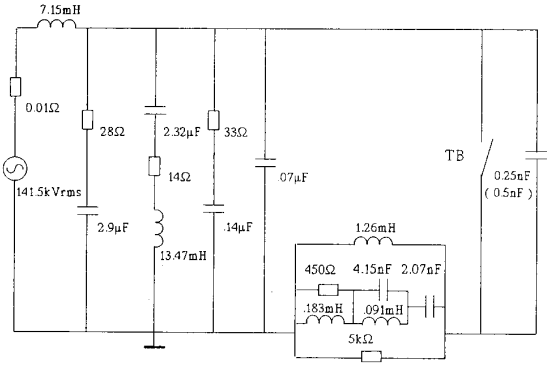


Figure 3
Direct SLF test circuit

interrupting interval, a correct triangular shaped recovery voltage from the SLF test is very important. For test circuits of figure 1, figure 2 and figure 3 the first excursions of the recovery voltage are plotted in figure 4. The voltage circuit injection moment is 20 μs after current zero for the series

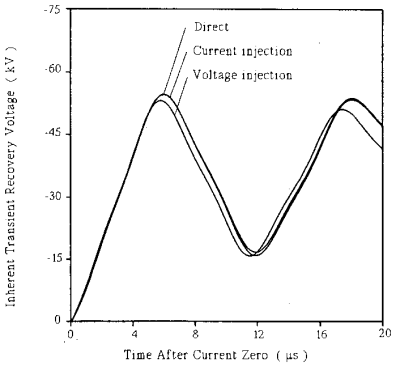


Figure 4
Inherent transient recovery voltage of the test circuits

voltage injection circuit of figure 1. The reduction of the peak voltage of the series voltage injection circuit is caused by the capacitive voltage division between TB and AB.

The same arcing time is assumed for the AB and TB in following calculations.

ARC VOLTAGE INFLUENCE IN THE HIGH CURRENT INTERVAL

The insertion of an AB in a synthetic test circuit introduces an extra arc voltage in that circuit. The arc voltages of TB and AB shorten the first current loop and extend the second current loop [3].

In synthetic test circuits the ratio of the driving voltage of the current source with respect to the arc voltages is low, because the driving voltage is a fraction of the rated voltage and the arc voltages of TB and AB add up. As a result, the duration of the first current loop and also the arc energy in the TB is reduced.

The arc energy reduction for the TB in the first current loop is shown in figure 5. E_s and E_d represent the total arc energy input in the TB in a series voltage injection synthetic test circuit (E_s) and direct test circuit (E_d). U_{rms} is the current source driving voltage and U_{arc}(AB+TB) is the sum of the arc voltages of the AB and the TB. For a trapezium-shaped and a linearly rising arc voltage, the U_{arc}(AB+TB) is the maximum attained voltage in the AB and the TB. Figure 5 is based on the assumption that the arc voltages in the AB and the TB have the same waveform.

The arc energy reduction in the TB varies with the arc duration (i.e. the arcing time of the TB). Figure 6 shows the change of arc energy reduction as a function of the arc

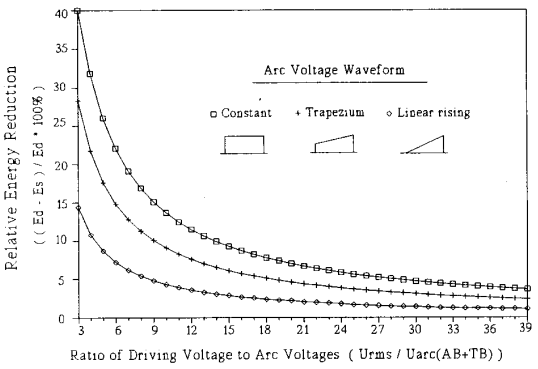


Figure 5
The total arc energy reduction of the TB in a synthetic test circuit with a one-current-loop arc duration

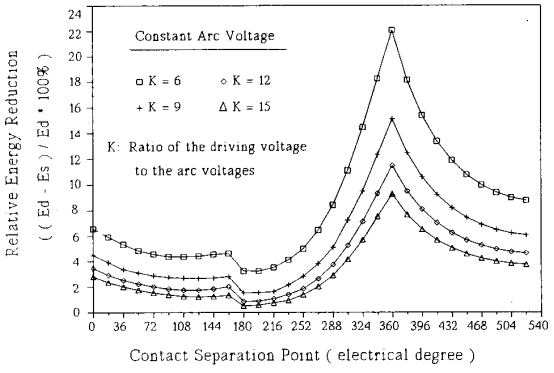


Figure 6
The relative arc energy reduction of the TB vs the arc duration in the synthetic test circuit

duration. In figure 6, the TB contact separates at zero electrical degrees and this corresponds to a TB with a three-current-loop arc duration. Contact separation at 180 electrical degrees corresponds to a two-current-loop arc duration and contact separation at 360 electrical degrees corresponds to a one-current-loop arc duration for the TB.

From figure 5 and figure 6 we learn that the total arc energy reduction in the TB in a synthetic test circuit mainly depends on the ratio of the current source driving voltage to the arc voltages in the AB and the TB. If the driving voltage is 15 times the arc voltage of the AB and the TB, the arc energy reduction in the TB is 9% for a constant value of the arc voltage. In the test circuit of figure 1, the sum of the arc voltages should not exceed 3.4kV, this being 6.8% of 50kV, to achieve this.

The curves of figure 5 and figure 6 are computed for a

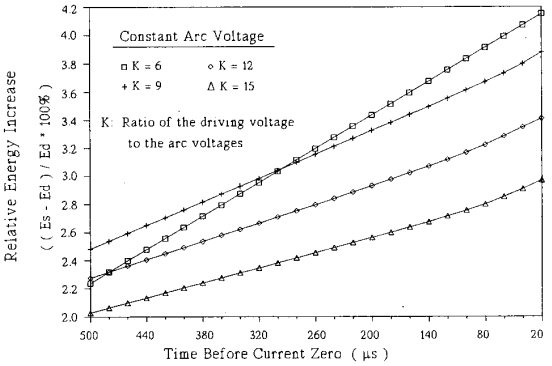


Figure 7
Arc energy increase before the first current loop zero instant in the voltage injection synthetic test circuit
Breaker rating: 245kV/63kA/50Hz, full pole

breaker rating of 245kV / 63kA / 50Hz full pole. The breaker rating has hardly any influence on the shape of the curves, so figure 5 and figure 6 can be used for other breaker ratings as well.

The arc voltages of the AB and the TB have an influence such that the dI/dt before the first current zero is higher than the dI/dt in the corresponding direct test circuit. A higher dI/dt means a higher arc energy input per time unit just before current zero. This means for the TB in the series voltage injection synthetic test circuit that, although the total arc energy input is lower, the arc energy input per time unit just before current zero is higher. Figure 7 shows the increase of the arc energy input in the voltage injection synthetic test circuit before the first current zero. The calculation is done in the time range of 20 μs up to 500 μs before current zero. The increase of the arc energy input in the TB just before current zero is inversely proportional to the ratio of the driving voltage to the arc voltages in the AB and the TB.

ARC VOLTAGE INFLUENCE DURING THE CURRENT ZERO PERIOD

For a small arc time constant, as in SF_6, the arc voltage just before current zero is important for the breakers. The arc voltage can influence the arc-circuit interaction and this can affect the interrupting capability of the breaker.

Depending on the interrupter design, there are several shapes of arc voltage waveforms for a breaker when it clears a fault current. One shape is the arc voltage with an extinguishing peak (figure 8), another shape is the arc voltage with a less significant extinguishing peak (figure 9) or an arc voltage without extinguishing peak (figure 10).

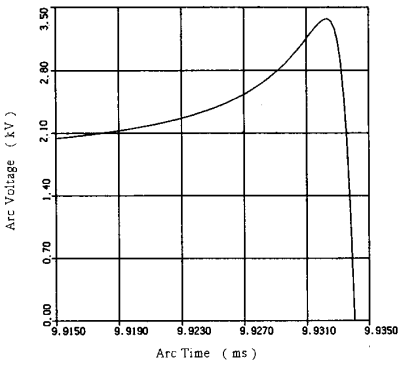


Figure 8
Arc voltage with a significant peak

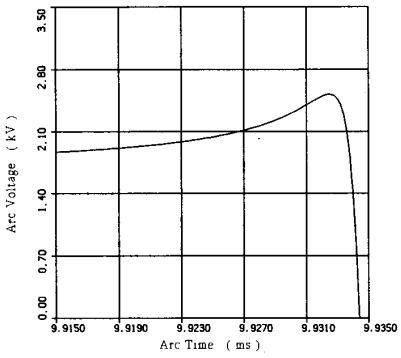


Figure 9
Arc voltage with a less significant extinguishing peak

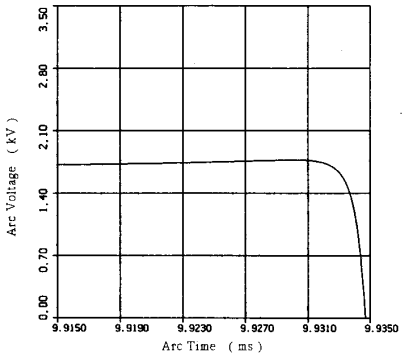


Figure 10
Arc voltage without extinguishing peak

It is assumed that the arc voltage in the high current interval has a value of 1.7 kV when the TB clears the SLF test in both the direct and synthetic test circuit. The different arc voltage waveforms in figure 8, 9 and 10 can be created using the KEMA arc model with the parameters of table 1 for the improved Mayr-model.

$$\frac{1}{G} * \frac{dG}{dt} = \frac{1}{\tau} * [\ \frac{I * U}{P * (P_0 + C_0 * |I|)} - 1\ ]$$

Table 1. Arc model parameter for fig.8, 9 and 10

Arc Voltage Waveform	Arc Model	P_0 (kW/bar)	τ (μs)	P (bar)	C_0 (V / bar)
Fig.8	I	33.0	0.8	6.5	262
Fig.9	II	20.0	0.8	6.5	262
Fig.10	III	10.0	1.0	6.5	262

For the calculation of the arc-circuit interaction, the arc models and the parameters of table 1 are used. The remanent energy at current zero in the TB arc channel is a result of the interaction between the breaker arc and the network. When a test circuit gives a high stress on the TB, the remanent energy in the TB will increase and the arc channel resistance, R_0, at current zero will decrease. By using the arc model we can calculate the R_0 of the TB in different test circuits. In the following section, we will compare the test circuits and the arc-circuit interaction by comparison of R_0.

ARC-CIRCUIT INTERACTION IN THE DIFFERENT TEST CIRCUITS

The TB arc channel resistance, R_0, at current zero is calculated for the test circuits of figure 1, 2 and 3.

Table 2. R_0 (Ω) of the TB for the different arc models in the different test circuits

Arc Model	Direct Circuit	Current Injection	Voltage Injection
I	612 654*	616 655*	546.5 576*
II	401 420*	402.5 422.5*	370 386.5*
III	170 173*	170 173*	164 165.5*

* C_b = 0.5 nF

Although the voltage injection synthetic SLF test circuit of figure 1, the current injection synthetic SLF test circuit of figure 2 and the direct SLF test circuit of figure 3 produce the same rated short circuit current, the arc-circuit interaction results in different values for R_0 of the TB during the actual test. The results of the calculation are shown in table 2. The influence of a grading capacitor and the stray capacitance of the TB is taken into account by C_b. The calculations have been done with two values of C_b: 0.25 nF and 0.5 nF.

INFLUENCE OF ADDITIONAL ARC VOLTAGE IN THE DIRECT TEST CIRCUIT

The presence of an AB in the test circuit introduces an extra arc voltage in the circuit. Table 3 shows the results of these calculations in a direct test circuit. In the direct test circuit, an AB with the same arc model parameters as the TB's is inserted. The arc channel resistance, R_0, of the TB at current zero is reduced by the AB. This means that an AB in a test circuit makes it more difficult for the TB to clear.

Table 3. R_0 (Ω) of the TB in the direct circuit and in the direct circuit with an AB inserted (C_b=.25nF)

	Arc Model (I)	Arc Model (II)	Arc Model (III)
Direct Circuit	612	401	170
AB Inserted *	571	383.5	168.5

* In the direct circuit with an AB inserted.

INFLUENCE OF ARC VOLTAGES IN THE VOLTAGE INJECTION TEST CIRCUIT

The same conclusion can be drawn from the calculation of the voltage injection synthetic test circuit of figure 1. In table 4, we can see when the calculations are performed with a closed AB, the R_0 of the TB increases for all three arc models. Table 4 shows that the R_0 of the TB varies for different arc models used to simulate the AB. When the AB has a significant extinguishing peak, the R_0 of the TB has a small value. This indicates that it is more difficult for the TB to clear. The R_0 of the TB increases when the extinguishing peak of the AB decreases.

Table 4. Influence of different arc models in AB and TB to the R_0 (Ω) of TB (C_b=.25nF)

Arc Model in AB	Arc Model in TB (I)	Arc Model in TB (II)	Arc Model in TB (III)
I	546.5	360	155.5
II	559	370	158
III	578	380.5	164
'	595	392.5	166.5

' AB is closed

Not only the shape of the arc voltage but also the steady state value of the arc voltages of AB and TB have an influence on the arc resistance R_0 of the TB. Table 5 shows

Table 5. Influence of the AB and TB arc voltages at the high current interval on the R_0 of the TB (C_b = .25nF)

U_{arc} (AB+TB) (kV)	8.3	5.5	4.2	3.4
U_{rms}/U_{arc}(AB+TB)	6	9	12	15
C_0 (V / bar)	638	423	323	262
R_0 (Ω)	896	682	598	546.5

Table 6. Influence of AB arc voltage at high current interval to the R_0 of TB (C_b=.25nF)

AB U_{arc} (kV)	4.26	3.4	1.7	0.85
C_0 (V/bar)	655	524	262	131
R_0 (Ω)	540	543	546.5	549.5

that the R_0 decreases with the increase of the ratio of driving voltage to the arc voltages. In table 5 and table 6, the arc model parameter C_0 (V/bar) represents the constant arc voltage in the high current interval. The other arc model parameters of arc model I are kept unchanged in the calculations. The series voltage injection synthetic test circuit of figure 1 is used for the calculations of table 5 and table 6.

Table 6 shows the results of the calculations when the arc voltage of the AB has different values of steady-state voltage. The arc voltage of the TB remains unchanged (1.7kV). The steady-state value of the AB has hardly any influence on the interrupting capability of the TB.

In table 7, the required minimum SF_6 pressure is taken as a parameter to compare the interrupting performance of the different arc models in the three test circuits. Increased minimum SF_6 pressure means that it is more difficult for the TB to clear. In the calculation of table 7, the same arc model parameters are used for both the AB and the TB.

Table 7. Minimum SF_6 pressure P (bar) for the TB to clear the SLF under different test circuits (C_b = .25nF)

Arc Model	Direct	Current Injection	Voltage Injection
I	6.50	6.42	7.27
II	6.50	6.43	6.83
III	6.50	6.43	6.62

The arc channel resistance at current zero is the result of arc-circuit interaction before current zero. At current zero, there is still a strong "arc-circuit" interaction because for SF_6 breakers, the channel resistance is of the same order of magnitude as the surge impedance of the connected network.

Table 7 gives the minimum SF_6 pressure necessary for the TB to clear the SLF in the different test circuits as calculated using the KEMA arc model.

From the calculations performed, we can conclude that the voltage injection synthetic test circuit puts more stress on the TB than the direct and current injection circuits do during the current zero period. The stress of the voltage injection circuit on the TB is less when the TB has a less significant extinguishing peak or no extinguishing peak at all.

CONCLUSIONS

- The total energy input in the TB in the synthetic test circuit is always lower than the energy input in the direct test circuit. The arc energy reduction in the TB in the synthetic test circuit depends on the arcing time. The maximum relative arc energy reduction for the TB occurs when the TB has an arcing time of one current loop.

- The higher the ratio of the driving voltage to the arc voltages, the less arc energy reduction during the high current period there will be for the TB in synthetic test circuit. When the ratio is 15 times the arc voltages in AB and TB the maximum relative energy reduction in the high current interval is 9%.

- Although the total arc energy input in the TB in the synthetic test circuit is lower than in the corresponding direct test circuit, the arc energy input to the TB a few hundred microseconds before current zero in the voltage injection synthetic test circuit is higher than in the corresponding direct test circuit.

- The AB in the voltage injection synthetic test circuit causes the overstress on the TB during the current zero period. The higher the extinguishing peak in the AB, the more difficult it is for the TB to clear.

- The steady-state value of the arc voltage in the AB during the high current interval hardly influences the arc-circuit interaction of the TB, but the extinguishing peak has a significant influence.

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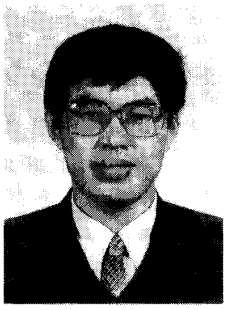
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