Modelling of Sf6 Circuit Breaker Arc Quenching Phenomena In Pscad

B. Kondala Rao, Gopal Gajjar
ABB Ltd., Maneja, Vadodara, India

Introduction

Circuit breakers play an important role in transmission and distribution systems. They must clear faults and isolate faulted sections rapidly and clearly. They are also used for normal load switching. Any circuit breaker designed should interrupt at natural current zero and withstand dielectric stresses caused during interruption. Depending on the extinguishing medium used, the circuit breakers are classified as oil, air blast, vacuum and SF6 circuit breakers.

SF6 is used as an extinguishing medium for high voltage circuit breakers. SF6 breakers are characterized by their superior dielectric properties, highest electrical endurance, reliability and availability, low noise level. SF6 puffer type circuit breaker is the breaker type used for the interruption of highest short circuit powers, up to 550 kV, 63 kA per interrupter [1].

The current interruption is performed by cooling the arc plasma so that the electric arc, which is formed between the breaker contacts after contact separation, disappears. At short circuit current zero, the instantaneous energy input to the arc is minimal, enabling the arc to extinguish. Immediately after the extinction of the arc, the power network reacts with a transient recovery voltage (TRV) that stresses the gap.

In PSCAD, breaker is used as a simple switch. With this switch the various phenomena that occur in breaker such as chopping current, multiple re-ignitions cannot be observed. So a detailed model of the breaker is required which replicates the original breaker characteristics. Normally, arc models are applied to problems such as determining a circuit breaker limiting curve for a SLF test or predicting current chopping while interrupting low inductive currents.

For SF6 breaker, various black box arc models have been proposed which give the possibility to extend the information obtained during the tests in a High power laboratory. The aim of the black box arc models is to describe the interaction of the switching arc and the corresponding electrical network during an interruption process. The black box arc models make use of the voltage and current traces from a circuit breaker test together with a given mathematical differential equation to deduce a mathematical model of the arc for that particular network conditions [2]. The developed model is then used to predict the interruption behaviour of the circuit breaker for all other network conditions.

Modelling Of SF6 Breaker

By modelling, it is meant that the model is characterized by experimentally measured parameters to describe the statistical properties of different phenomena taking place in the breaker opening process. Various black box arc models have been proposed which give the possibility to extend the information obtained during the tests in a High power laboratory.

The flow chart for the application of Black box arc models is as shown in Figure 1. For the accurate analysis, practical values of the breaker parameters obtained from real experiment are to be provided for the model as explained in the flowchart. As these values are not available, some tentative values have been considered.

Black box arc models are mathematically expressed as formulae for the time varying arc conductance as a function of arc current, arc voltage and several constant or time varying parameters representing arc properties.
Cassie model

In 1939, A. M. Cassie has proposed an arc model [1] with the assumptions that the arc channel has the shape of a cylinder filled with highly ionized gas with a constant temperature \( T \), but with a variable diameter. He further assumed that the heat content per unit volume remains constant and so does the conductance per unit volume. Cassie model is well suited for studying the behaviour of the arc conductance in the high current time interval.

Mayr model

In 1943, O. Mayr assumed power losses are caused by thermal conduction [1] at small currents. This means that the conductance is strongly temperature dependent but fairly independent of the cross-section area of the arc. The area is therefore assumed constant. The electrical conductivity varies exponentially with the temperature. He further assumed that the power loss of the arc channel is constant. Mayr model is well suited for modelling arc in the vicinity of current zero.

### Mathematical Model

\[
\frac{1}{g} \frac{dg}{dt} = \frac{1}{\tau_m} \left( \frac{ui}{P_o} - 1 \right)
\]

where

- \( g \rightarrow \text{Arc conductance} \)
- \( u \rightarrow \text{Arc voltage} \)
- \( i \rightarrow \text{Arc current} \)
- \( P_o \rightarrow \text{Cooling Power} \)
- \( \tau_m \rightarrow \text{Time constant (Rate at which arc is extinguished)} \)

### Implementation of Breaker Model

The electric arc has been simulated in PSCAD as a “black-box” model. The external electrical circuit sees the arc as an equivalent electrical conductance that changes with time and other physical variables.

As the transients occur in breaker in the range of microseconds, the time step for simulation should be sufficiently less to observe the effect of transients in the breaker. The simulation time considered is in the range of 0.1 _s_.

### Testing of Breaker Model

The breaker model developed is tested to validate its accuracy for Short Line Fault clearing and switching of low impedance currents. The breaker parameters considered in both the cases are not specific to a particular make or from real experiments.

### Short Line Fault (SLF)

SLF is the critical fault, which occurs on a transmission line within some distance (a few km) from the breaker. The most severe stresses occur in the case of relatively short lines some km in length[3]. This voltage arises from the trapped energy on the line section between the breaker and the fault location.

Because cables and overhead lines have distributed constants, the breaker line side voltage oscillates in the form of a traveling wave. The line side component of the recovery voltage has a saw-toothed shape and a high rate of rise[4]. As seen earlier, the source recovery voltage rises much more slowly and only the line side triangular recovery voltage is important during the early portion of the TRV.

The SLF test is performed only for the single-phase circuits. It is more severe in this case only. These faults have currents close to the CB rating and have an appreciable source side transient and a line side transient given by the short length of the line between the breaker and the fault.

As the fault location moves away from the breaker, the fault current decreases and the Rate of rise of recovery voltage (RRRV) decreases.
To validate the accuracy of this model for short line fault, three cases have been considered showing the effect of the load capacitance, effect of the fault location and the effect of the cooling power.

For the present case, the load side capacitance is reduced from 1.1nF to 1.1pF. The RRRV has increased from 9.243 kV/s to 9.575 kV/s.

Effect of the fault location
The length of the line has been reduced from 1.5km to 1.2km keeping all other parameters constant. In this case, the TRV monitored is as shown in Figure 6.

Effect of source and load capacitances
The source side capacitance provides the time delay prior to the initial rate of rise of the source side TRV. The purpose of line side capacitance is to provide time delay prior to the initial rate of rise of the line side TRV. The variation of RRRV with line capacitance is shown in Figure 5.

For this case, the peak value of the ITRV observed is 73.36 kV. The peak value of the fault current is 49.05 kA.
In this case, the breaker has failed to interrupt the arc.

From Figure 7, it is observed that as the fault location is reduced from 1.5 km to 1.2 km, the severity of the fault has been increased and the breaker has failed to interrupt the arc. For the reduced fault distance, the RRRV is 9.928 kV/s.

Effect of cooling power

From Mayr model, it is known that for constant \( m \), as cooling power (Po) is increased, \( (ui/Po) \) will be less than 1 and the rate of change of conductance will have better response as shown in Figure 8 and Figure 9. The cooling power is decreased from 293 kW to 250 kW keeping all other parameters constant.

The value of conductance just before current zero influences the breaker in its interrupting ability[6]. So the conductance before the current zero is compared in both the cases as shown in Figure 9. Lower the conductance value better is the interrupting ability.

With the reduced cooling power, the breaker has failed to interrupt the arc. Hence the minimum cooling power required to interrupt the arc for various fault locations is found and is shown in Figure 10.

In Figure 11, a graph is plotted between conductance at 200ns before current zero and the test case. It is
observed that for all the cases where $G(-200 \text{ ns}) > 2.5 \text{ mS}$, the test resulted in re-ignition and $G(-200\text{ns}) < 2.5 \text{ mS}$, resulted in successful interruption.

**Interruption of Low Inductive currents**

Interruption of low inductive currents occurs when unloaded transformers are taken in and out of service, motors are disconnected, or electric furnaces are switched. When an interrupting device interrupts a small inductive current, the current can be interrupted at a short arcing time. The gap between the arcing contacts, after current interruption, is rather small and the capability to withstand dielectric breakdown is relatively low[1].

The interruption of low currents leads to situations known as current chopping and virtual current chopping. These phenomena lead to high frequency oscillations through the arc channel, thus forcing a zero crossing before the actual power frequency current zero. When the breaker interrupts this high frequency current, the resulting TRV has an extremely high peak value and these overvoltages lead to multiple re-ignitions.

![TRV plot](image)

To validate the accuracy of this model, three cases have been considered showing the effect of the load capacitance, cooling power and arcing time.

Initially the cooling power is considered as 15 kW and the time constant is considered as 0.5 s. The rated voltage of the system is 245 kV (peak).

For the given circuit parameters, the TRV and the breaker current waveforms are as shown below.

**Effect of the load capacitance**

When the current interruption is successful at current zero, the voltage across load capacitance is zero, and the TRV building up across the breaker contacts charges first the load capacitance, which causes the so called time delay of the TRV waveform.

The chopping current magnitude is further dependent on the load capacitance. By increasing the load capacitance from 5 nF to 10 nF, the chopping current has been almost doubled as shown in Figure 14. The rate of rise of TRV (RRRV) has been reduced from 2.6 kV/s to 1.8 kV/s.

![Comparison of breaker current plots](image)
Effect of the cooling power

By increasing the value of the cooling power from 15 kW to 30 kW, the chopping current magnitude increased from 9A to 20A. This results in the increased stress between the contacts. So the peak value of the TRV has increased from 248 kV to 305 kV. The TRV and the current plots for different cooling power are shown in Figure 15. Higher the cooling power, higher is the chopping current magnitude.

Effect of arcing time

The arcing time of the breakers is the time between the contact separation and the corresponding current zero. As the arcing time is increased, the magnitude of the TRV gets on reducing. The closer the breaker contacts open to current zero, the higher the chopping current magnitude.

Conclusions

Mayr arc model with constant time parameter and cooling power is implemented to develop SF6 breaker model in PSCAD. From the SLF test, it is observed that for the successful interruption of the arc, the fault location should be within the critical length, cooling power should be optimal for the given fault location and the presence of the capacitances across the breaker is required. For the interruption of inductive currents, the various factors that affect the TRV are studied in detail.

It can be concluded that the breaker model developed can be used to design the arc quenching power of the breaker to meet the SLF requirement.

REFERENCES