Overvoltages and reignition behavior of vacuum circuit breaker

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***Abstract* –Vacuum circuit breakers (VCB) have excellent interruption and dielectric recovery characteristics, and can interrupt the high frequency currents which result from arc instability, superimposed on the line frequency current. The interruption of these high frequency currents is called virtual current chopping, and can lead to repeated reignitions when the breakers are opening, resulting in severe voltage escalations under certain network conditions. In order to estimate the probability of such transients, a mathematical breaker model has been developed in ATP / EMTP. The model incorporates the random nature of arcing time, current chopping, dielectric strength and the quenching capability of the breaker. The performance of forty-eight representative of breakers (four kinds of dielectric strength and four kinds of quenching capability with three different time ranges of the opening of the breaker) with specific network were analyzed and the results are presented in this paper.**

Keywords – EMTP, Transient analysis, Vacuum circuit breaker, Overvoltage

I. INTRODUCTION

When a vacuum circuit breaker is opened, an electric arc is struck and ideally the arc extinguishes at a natural current zero. However, arc instabilities may lead to very high-frequency oscillations of the breaker current which superimpose on the power frequency current, causing this current to pass through zero before a natural current zero.

Vacuum circuit breakers are capable of interrupting currents with a very high di/dt, typically in the range of 150 - 1000A/μs [3] and consequently the high-frequency current may be interrupted during one of the high frequency excursions through zero. This is known as virtual current chopping. The breaker recovers only to reignite again when the system transient recovery voltage (TRV) exceeds the dielectric strength of the short gap of the interrupter. This can repeat a number of times, until the instantaneous level of the power frequency current becomes greater than the peak of the transient oscillatory current, when no further high-frequency current zeros occur, and the full arc is re-established. This interruption process can produce undesirable steep-front high voltage surges, which depends on the high frequency properties of the circuit, and the commutation ability of the breaker.

A few different mathematical breaker models exist and they all take into account arc thermal instabilities. However, there is no existing universal precise arc model because of the complexity of the arc physics. Many of these models are characterized by experimentally measured parameters to describe the statistical properties of different phenomena taking place in the breaker opening process.

This paper focuses on the modeling and simulating the escalation voltages and reignition behavior of vacuum circuit breakers. They were developed in ATP / EMTP by using MODELS. Rather than being based on measured parameters, the model chooses random values from a range of typical values for the each related variables during simulation, in order to determine the statistical overvoltages that may result for vacuum circuit breaker switching. The performances of forty-eight representative breakers with specific network were analyzed and the results are presented in this paper.

II. STATISTICAL VACUUM CIRCUIT BREAKER MODEL

The vacuum circuit breaker can be modeled with a variable arc resistance. [1, 4] Alternatively, the breaker can be represented by an ideal switch, [2, 3, 5] as shown in Figure 1, where its states are only characterized by the two possibilities “open” or “closed”.

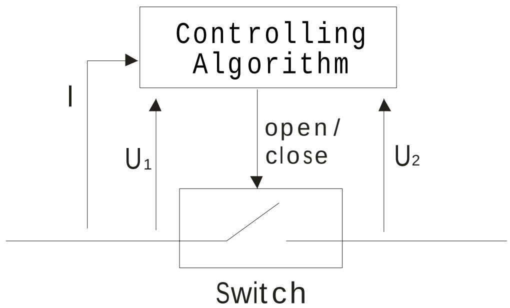

Figure 1 Model of Vacuum Circuit Breaker

The generic model incorporates different stochastic properties inherent to the breaker operation to control the actual state of the breaker during the computer simulation by considering different properties of the breakers:

- The random nature of arcing time
- The ability of the breaker to chop the current before its natural zero
- The characteristic recovery dielectric strength between contacts when opening
- The quenching capability of high frequency current at zero crossing

After the contacts of the breakers mechanically open, the dielectric strength between them increases as a function of time, and a 'race' between the transient recovery voltage and the dielectric strength develops. When the TRV exceeds the dielectric strength, a closing signal is sent to the switch, so that a reignition is simulated. Reopening can occur if the quenching capability (rate-of-change of the current at a current zero) has a value lower than the critical value and an opening signal is sent to the switch. If this extinction is followed by a new reignition, the above procedure starts again until the dielectric strength between the contacts can withstand the TRV.

A. Arcing time

The arcing time of the breakers is the time between the contact separation and the following current zero and it is random in nature. In this paper, three ranges of arcing time have been investigated: 0 - 100μs, 100 - 200μs, 200 - 300μs. A Gaussian distribution was used to represent the random nature of the arcing time.

B. Current chopping

The actual chopping current is non-deterministic, however earlier research established different mean chopping levels [3, 4] for different load currents and contact material. In this paper, the mean chopping current is estimated according to [3]:

$$\overline{I_{ch}} = (\omega \cdot \hat{i} \cdot \alpha \cdot \beta)^q \qquad (1)$$

with $\omega = 2 \cdot \pi \cdot 50Hz$

$\hat{i} =$ amplitude of the 50 Hz current

$\alpha = 6.2 \cdot e^{-16} s$

$\beta = 14.3$

$q = (1-\beta)^{-1}$

The chopping currents derived from this equation correspond to those of modern vacuum circuit breakers, which use Cu/Cr contacts. The chopping current depends on the moment of separation of the contacts: the closer the contact opens to current zero, the higher the chopping current. In our simulation the statistical nature of the chopping current is represented by a Gaussian distribution with 15% standard deviation from the calculated value of equation (1). The breaker current is assumed to be chopped immediately once the absolute value of the current exceeds the statistically determined value.

C. Dielectric strength

There are two breakdown mechanisms [3]: the first one is the breakdown of a cold gap, while the second one refers to a gap which has reignited, such that residual charge carriers exist near the cathode and the breakdown occurs at lower voltages. In this paper, only the cold gap breakdown is considered and the literature shows that a linear dependency of dielectric strength and contact distance can be assumed [3, 5]. A typical relation is as follows:

$$U = A(t - t_{open}) + B \qquad (2)$$

where t_{open} is the moment of contact separation. The values of the constants A and B in (2) for four typical dielectric strength characteristics are shown in Table 1.

A (V / μs)	B (V)
2	0
20	0
30	1000
50	0

Table 1 Dielectric strength of VCB

The value of U calculated with (2) is assumed to be the mean value of a Gaussian distribution with a standard deviation of 15%.

D. High frequency quenching capability

A reignition occurs when the TRV exceeds the dielectric strength of the breaker contacts. The actual frequency of the high frequency current associated with arc stability of the breaker is determined by a model comprising inductance and capacitance. This high frequency current will superimpose on the power frequency current. When the high frequency current gets larger in magnitude than the power frequency current, it can force current zeros at times other than those expected to occur normally with power frequency current. Most vacuum circuit breakers have the ability to quench this high frequency current and therefore the current may be quenched in one of its zero crossings at high frequency.

The rate-of-change of the current at a current zero determines whether or not there is a successful extinction. The high frequency quenching capability of typical vacuum circuit breakers is found in the range of several hundred A/μs [3]. This value can be a constant or a function of the time after contact separate as shown in equation (3):

$$\frac{di}{dt} = C(t - t_{open}) + D \qquad (3)$$

where t_{open} is the moment of contact separation. The values of the constants C (which can be positive or negative) and D are shown in Table 2. It is assumed that when the absolute value of the rate-of-change of the current at a current zero above this di/dt limit, arc extinction will not occur.

C (A / μs^2)	D (A / μs)
-0.34x10^5	255
0	100
0	600
0.31x10^6	155

Table 2 Quenching capability of VCB

Combining the current chopping, dielectric strength and the quenching capability characteristics of the breaker leads to sixteen different breaker models. Incorporation of the random nature of the arcing time results in a total of forty-eight models, which were developed and analyzed.

E. Type of termination

When a vacuum circuit breaker reignites during an open operation, voltage escalation occurs and the interruption process can terminate in one of three ways:

- The breaker can successfully interrupt at the end of the high frequency reignition sequence. The gap successfully recovers after a series of restrikes. This is referred to termination mode A.
- The breaker fails to interrupt the high frequency current, the power frequency current takes over and the final interruption is accomplished at the next power frequency current zero. This is designated a termination mode B.
- The breaker fails to interrupt and may cause harm to itself and/or connected equipment.

III. IMPLEMENTATION OF THE VACUUM CIRCUIT BREAKER MODEL IN EMTP

The basic model of the circuit breaker incorporates a circuit similar to the one proposed by J. Helmer [3]. The circuit shown in Figure 2 can be interpreted as a representing a typical medium voltage industrial supply network where critical transient situations may occur, and is expected to produce the most severe overvoltages.

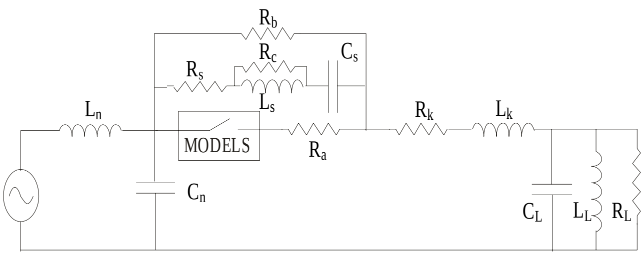

Figure 2 Helmer's circuit

where

	L_n = 5mH	C_n = 0.1μF
R_S = 50Ω	L_S = 50nH	C_S = 200pF
R_k = 2Ω	L_k = 40μH	
R_L = 10kΩ	L_L = 120mH	C_L = 10nF
R_a = 1x10^{-5}Ω	R_b = 9500Ω	R_c = 1.33Ω

Resistor R_b was included to account for the natural damping that occurs in practice. The value chosen was the largest possible to provide effective damping without undue influence on the natural behavior of the switch. R_a has a negligible value and is there for current measuring purposes for MODELS. R_c is connected across inductor L_s to damp numerical oscillations which are brought about by the current interruption.

The results show in Figure 3, 4 and 5 are based on one of the breaker models of the forty-eight representative breakers. In this case, the rate-of-change of the dielectric strength was chosen to be 50 V/μs while the quenching capability was set to 100 A/μs. The voltage across the breaker oscillates at a high frequency immediately after current interruption at about 0.7ms. This oscillation is a result of interaction between the longitudinal capacitance of the breaker C_S, the parasitic capacitance to ground at the load side of the breaker C_L and the cable inductance L_k.

The frequency is given by:

$$f_1 \approx \left(2 \cdot \pi \cdot \sqrt{L_k \cdot \frac{C_S \cdot C_L}{C_S + C_L}}\right)^{-1} \approx 1.8\text{MHz}$$

Following the decay of the initial transient, a much lower frequency dominates. This is caused by the interaction of the load stray capacitance C_L and the inductive load L_L. The frequency is given by:

$$f_2 \approx \frac{1}{2 \cdot \pi \cdot \sqrt{L_L \cdot C_L}} = 4.6\text{kHz}$$

Had there be no reignition, the TRV would have risen to a magnitude given by:

$$V = I_{ch}\sqrt{\frac{L_L}{C_L}} = 21.3\text{kV}$$

However, if the TRV exceeds the dielectric strength of the breaker, re-ignition will occur as shown in Figures 3d.

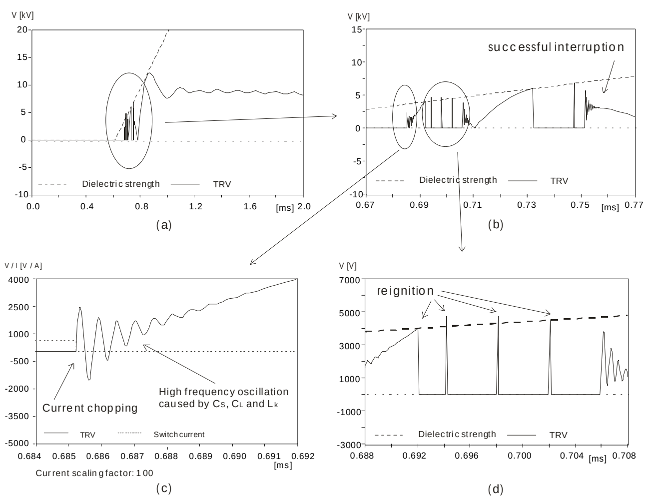

Figure 3 TRV waveform

The arc re-establishes and current starts to flow through the gap. The current waveshape comprises two frequency components as show in Figure 4.

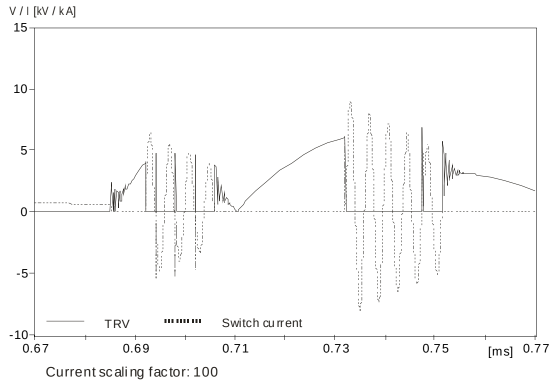

Figure 4 Arc Re-establishment

The first one is a result of interaction of L_S and C_S and the second one is a result of interaction of L_k and C_L. The first frequency component I_{f3} is:

$$f_3 \approx \frac{1}{2 \cdot \pi \cdot \sqrt{L_S \cdot C_S}} \approx 50\text{MHz}$$

Owing to the high frequency, this component is quickly damped and is not quenched at its zero crossing. The second frequency component I_{f4} now becomes dominant and its frequency is given by:

$$f_4 \approx \frac{1}{2 \cdot \pi \cdot \sqrt{L_k \cdot C_L}} \approx 0.25\text{MHz}$$

This second frequency component is interrupted at a zero-crossing and the TRV rises again. As this process repeats, the magnitude of TRV escalates at each re-ignition owing to the increase of stored energy in the inductors from previous re-ignitions.

Also, the dielectric strength is increasing during the whole process since the contacts are separating and once the contacts become sufficiently far apart the dielectric strength prevails over the TRV and no more re-ignitions take place. This is shown in the Figure 5.

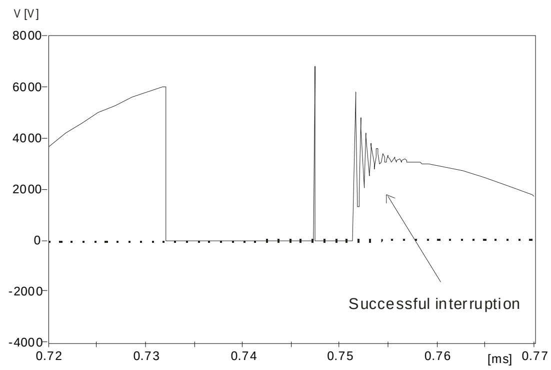

Figure 5 Successful interruption

When the rate-of-change of the dielectric strength is decreased to 30 V/μs while keeping all the other parameter as the same as the pervious case, the termination mode changed from type A to type B. As shown in Figure 6, the current cannot be interrupted at high frequency and the conduction period of the high frequency component was lengthened to around 3 ms, also the number of reignitions increased.

As the reignitions repeat, eventually a point must be reached when the power frequency current is greater than the high frequency current. Then, the conduction period is diminished and the power frequency conduction resumes, and there can be no recovery until the next power-frequency based current zero.

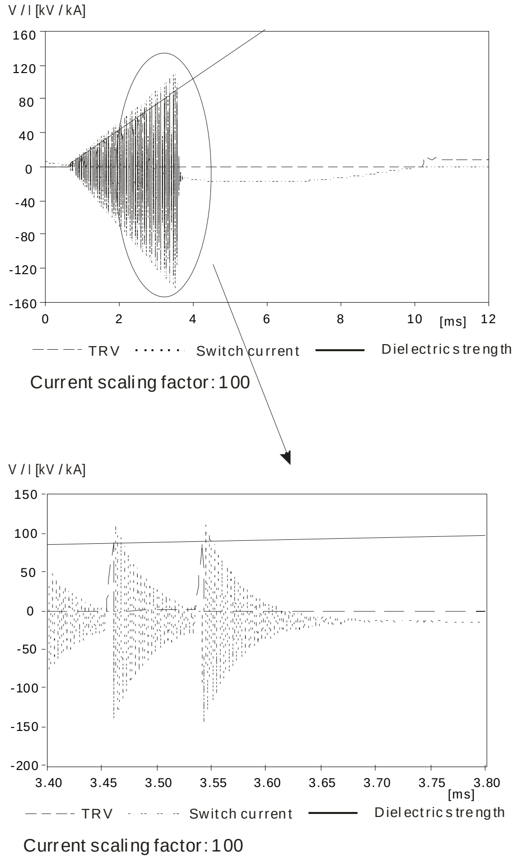

Figure 6 Unsuccessful interruption

IV. DISCUSSION

This paper examines the reignition behavior of vacuum circuit breaker EMTP models with several combinations of dielectric strength, quenching capability and arcing time. To take into account the statistical character of the breakers, a Monte Carlo method is used. One hundred cases for each combination have been examined with the network shown in Figure 2.

When the rate-of-change of the dielectric strength is gradually decreased from 50 V/μs to 2 V/μs, with all other characteristics and parameters remaining constant, the escalation voltage will increase until the termination mode changes from mode A to mode B [2] as illustrated in Figure 7.

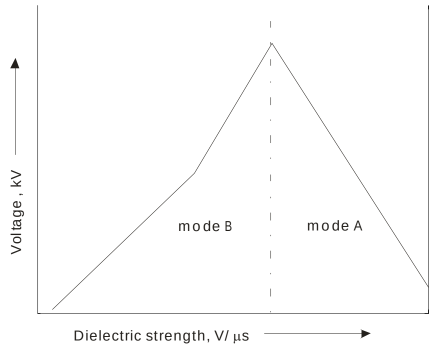

Figure 7 Recovery voltage vs dielectric strength

In termination mode A, it was found that the conduction period of high frequency current I_{f4} is longer when the rate-of-change of the dielectric strength decreases from 50 V/µs to 20 V/µs as shown in Figure 8. Consequently, the voltage escalates and more reignitions occur.

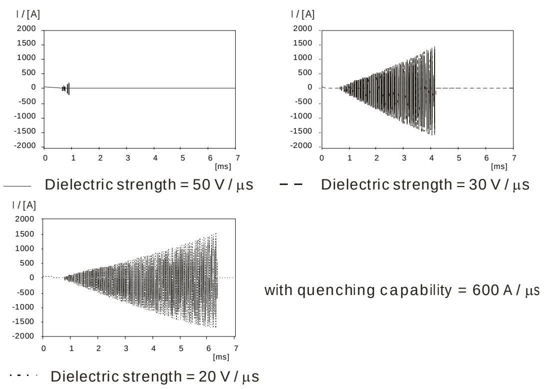

Figure 8 The current pattern

On the other hand, when considering termination mode B, it was established that the higher the rate-of-change of the dielectric strength, the higher of the magnitude of the high frequency current I_{f4} and the longer its conduction period, as illustrated in Figure 9.

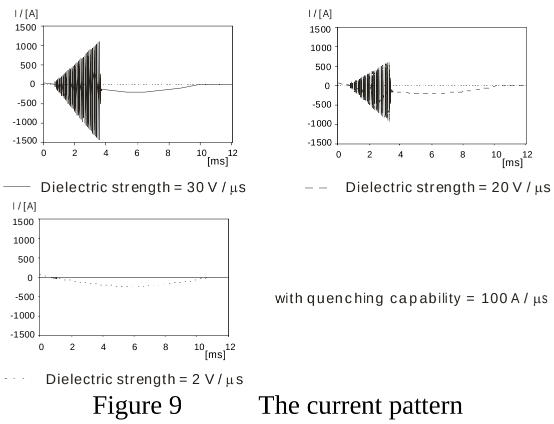

Figure 9 The current pattern

Consequently, the escalation voltage is most severe when the rate-of-change of the dielectric strength is in the middle range between 50 V/µs and 20 V/µs.

The variation of the quenching capability also affects the interruption of the high frequency current. As show in Figure 10, the higher the quenching capability, the higher the TRV and more reignitions occur. On the other hand, when the quenching capability is too small, the current may not be chopped during the high frequency period and this will result in failure of interruption. Additionally when the quenching capability decreases to zero, the breaker will fail to interrupt.

When comparing the influence of the quenching capability with the rate-of-change of the dielectric strength on the escalation voltage, it was found that the effect of the quenching capability is not as significance as the rate-of-change of the dielectric strength. The quenching capability affects the termination mode of breakers with the same dielectric strength. When the quenching capability is large, the termination mode is likely to be mode A. Consequently, the peak of the characteristic shown in Figure 7 shifts when the quenching capability varies.

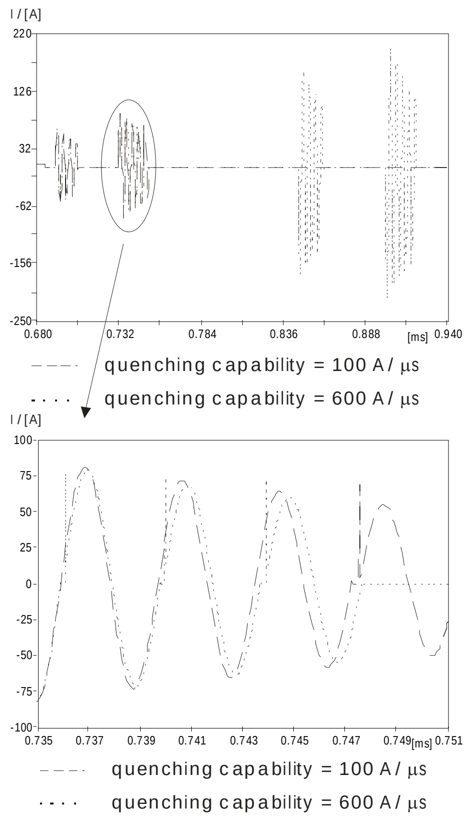

Figure 10 The current pattern with variation of the quenching capability

Figure 11 summarizes the effect of the rate-of-change of the dielectric strength and the quenching capability of the vacuum circuit breaker models with different arcing time ranges on the escalation voltage. When the rate-of-change of the dielectric strength is between 20 and 30 V/µs (middle range), the escalation voltage is usually higher than other cases. However, when the arcing time is close to the current zero (ranging from 0 – 100 µs), the escalation voltage is more severe than those arcing time ranging from 100 µs to 300 µs. Also, high escalation voltage usually appears when the quenching capability has a negative slope.

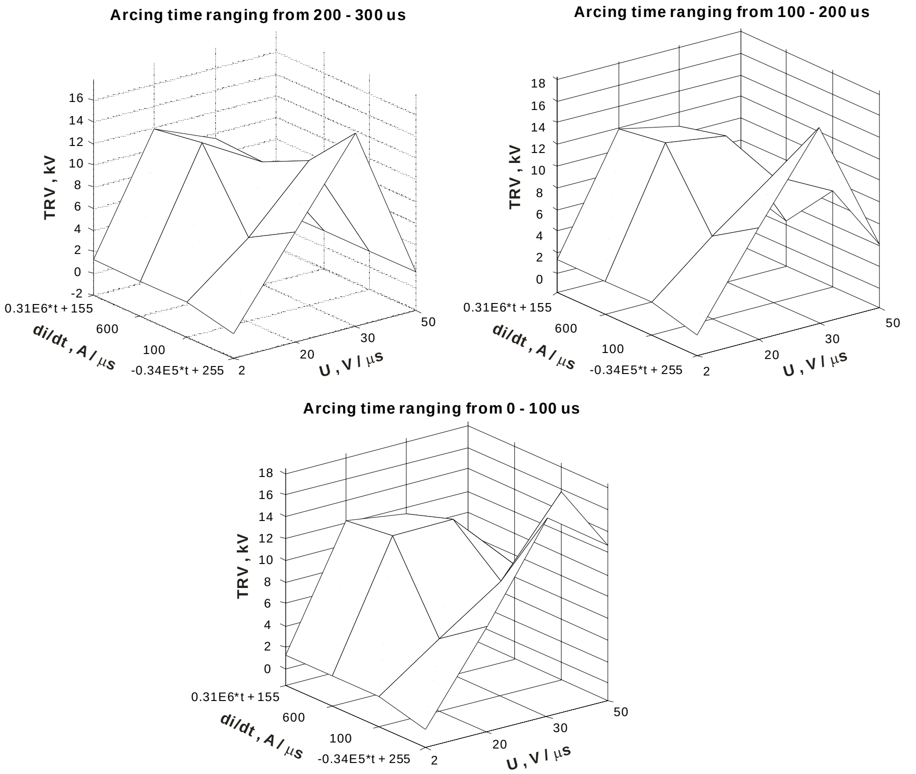

Figure 11 Escalation voltages as a function of the breaker model characteristics

V. Conclusions

A stochastic model of vacuum circuit breakers was developed and used in EMTP to study system overvoltages resulting from virtual current chopping. The statistical properties of the arcing time, chopping current, dielectric strength, and quenching capability were taken into account and forty-eight breaker models are applied to study the TRV generated under different switching conditions.

Some combinations of the breaker characteristics may lead to reignition/voltage escalation problems. For example, high escalation voltages are more likely to occur when the arcing time is short, or the dielectric strength is in the middle range, or the termination mode is mode A (successfully interrupt at the end of the high frequency reignition sequence), or if the quenching capability decreases with time.

The result of the statistical TRV calculation shows that the rate-of-change of the dielectric strength and the arcing time of the breaker are the most important for the estimation of the TRV, while the influence of the quenching capability on the escalation voltage is less pronounced.

Consequently, when estimating the overvoltages resulting from the operation of vacuum circuit breakers in the system, it is suggested to consider the middle range of the rate-of-change of the dielectric strength to look for the worst case in order to provide the most appropriate protection scheme.

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