

Article

Influence of Network and Arc Parameters on the R500 Interruption Limit of High-Voltage Circuit Breakers

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Abstract

A systematic investigation of how different circuit and arc parameters affect the threshold value for the R500 interruption limit ($R500_{th}$) has been provided. These parameters include the breaker cooling power, arc time constant, time delay of the transient recovery voltage (TRV), parallel capacitance, and network impedance. The results are obtained through black-box model calculations based on Mayr's arc model. Our findings suggest that the interruption limit for the R500 method has negligible dependency on the cooling power used in Mayr's arc model. On the other hand, it is shown that larger values of parallel capacitance and TRV time delay led to a decrease of the $R500_{th}$. On the contrary, $R500_{th}$ rises by increasing the network impedance. These results imply that the influence of arc-circuit interaction must be considered when applying this approach for assessing the interruption limit. As a validation step, the numerical findings have been cross validated by selected measurement results provided in the literature.

Keywords: high-voltage circuit breaker; arc resistance; current interruption; Mayr model; black box arc modelling

1. Introduction

High-voltage circuit breakers (HVCB) are key components in electrical power systems, used to protect high-voltage equipment when a fault occurs in the grid [1–4]. During normal operation, the contacts of the HVCBs remain in the closed position, allowing the current to flow. However, as soon as a fault is detected, the contacts of the breaker are separated by the operating mechanism. This leads to the formation of an electric arc between the arcing contacts [5–8], which has to be extinguished and cooled down quickly and efficiently, so that the current is stopped and the fault is isolated from the rest of the system. The breaker's ability to interrupt the fault current, or in simpler terms, its interruption performance, is a measure determining how well the arc interruption process takes place. A higher interruption performance generally enables interruption of fault currents with a higher magnitude [9–14].

In recent years, the short circuit current in the network has significantly increased with the rapid expansion of power grids [15–17]. Accordingly, the interruption capability of the HVCBs had to be improved, so that they could successfully interrupt the increased fault current. Accomplishing this goal starts with a precise method, tool, or model that can be employed for the characterization of the interruption process.



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A well-known approach to evaluate the interruption outcome of HVCBs is based on evaluating the arc resistance behavior close to current zero [18,19]. In particular, a higher arc resistance close to current zero indicates a more efficient power dissipation from the arc column, leading to a better arc interruption. The arc resistance (R) (or equivalently conductance ($G = 1/R$)) corresponding to 500 ns or 200 ns before current zero has been proven to effectively characterize the outcome of the thermal interruption process in the context of high-voltage gas circuit breakers [3]. Numerous studies have demonstrated that, by plotting the arc resistance of the breaker at 500 ns (or 200 ns) before current zero (referred to as R_{500} or R_{200}) versus the interruption outcome (clear or fail), one can distinguish a clear boundary between successful and failed operations [18]. More specifically, a threshold line can be found when grouping the interruption outcome based on their R_{500} or R_{200} values. This threshold value is dubbed $R_{500_{th}}$. Successful operations correspond to R_{500} values residing above $R_{500_{th}}$, whereas failed operations cluster below the threshold value. In this regard, the proximity to the threshold line indicates that the breaker has been operated close to its interruption limit. In such cases, a small variation in the system or breaker parameters can change the outcome of the interruption process.

The R_{500} method has been widely used to characterize the interruption condition during critical test duties such as short line faults (L90/L75), where most failures are primarily driven by thermal runaway rather than dielectric breakdown. Existing studies based on empirical data indicate that the threshold value for the R_{500} classification method does not depend on the breaker design [3]. In particular, the same threshold value has been observed regardless of the circuit breaker design. However, the critical arc resistance required for successful interruption has shown dependency on the background gas mixture: higher values have been reported for CO_2 -based gas mixture compared to standard SF_6 -based mixture [20]. Despite this knowledge, little is known regarding the influence of circuit parameters on $R_{500_{th}}$. As the breakers' capability to interrupt is greatly influenced by the external circuit, one may naturally question whether the threshold value for the R_{500} -based interruption method is affected by such interactions, and if so to what extent.

In this paper, the influence of various circuit characteristics on the $R_{500_{th}}$ has been investigated through a series of numerical calculations based on Mayr's arc model. More specifically, we evaluate how the threshold value for the interruption criterion is affected by various factors, including time delay of transient recovery voltage (TRV), the presence of parallel capacitance, and network impedance. The results not only explain previously reported empirical observations in a systematic manner, but are also of great importance for modelling the current interruption process in high voltage circuit breakers. Such knowledge not only establishes a pathway toward the design and development of circuit breakers with enhanced interruption performance, but also is of importance for emerging applications and breakers operating in complex network topologies, such as HVDC systems, where reliable fault interruption is crucial [21].

2. Methods

To investigate the current (thermal) interruption process, one can employ the so-called black box modelling method [22–31]. In this method, the arc is usually described by a nonlinear and time dependent conductivity. The latter is usually described by an equation involving measurable electrical parameters, such as voltage and current, as well as fitting parameters optimized to replicate the arc behavior. A well-known example, introduced by Otto Mayr in 1943 [32], is Mayr's arc model, which is widely used for analyzing the arc interruption process in circuit breaker simulations. In this model, the conductivity of the arc is expressed according to the following equation:

$$\frac{1}{G} \frac{dG}{dt} = \frac{1}{\tau} \left(\frac{I \cdot V}{P} - 1 \right) \quad (1)$$

where G is the arc conductance, I and V are current and voltage, respectively, P is the cooling power, and τ is the arc time constant. While there exists a physical interpretation for the parameters P and τ , they can be thought of as optimization parameters that are swept to replicate the actual voltage (and potentially current) signals measured in the experiment.

The key novelty of the paper lies in applying Mayr's arc model to systematically investigate the $R500$ interruption criterion through circuit simulations, and comparing the results with empirical data. The circuit simulations have been conducted with MATLAB R2024b Simulink and ATP-EMTP tools. Figure 1 represents the sketch of the schematic of the used circuit, including high current (HC) and high voltage (HV) parts. The high current part provides the large current that the breaker faces during short circuit conditions. The high voltage part, on the other hand, generates the large transient recovery voltage appearing across the terminal of the breaker after current interruption. By properly adjusting the charging voltage of the capacitors and test circuit elements, both high current and voltage waveforms can be controlled. As an example, the current rate of rise at current zero (referred to as di/dt), can be simply controlled by tuning the charging voltage of the C_{HV} element in the test circuit. Obviously, a larger di/dt implies more severe conditions for the current interruption, while a smaller di/dt increases the probability of successful interruption. In fact, there exists a maximum value of the applied di/dt that a circuit breaker can interrupt, all other conditions being equal. This limit can be identified by changing the charging voltage of the capacitor bank C_{HV} around the interruption limit and recording the associated outcomes. It is important to note that while an increase in the charging voltage enhances the corresponding di/dt , it also affects the peak value of the TRV in the test setup under consideration. Later in the paper, we also examine a scenario where only di/dt varies, while the peak value of the transient recovery voltage (TRV) remains unchanged.

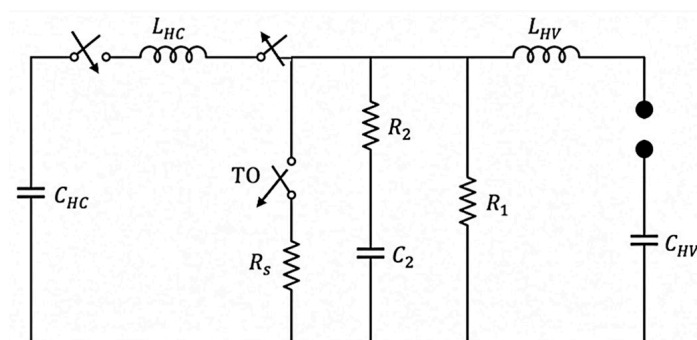


Figure 1. Test circuit used in the analysis. The test circuit includes the high voltage (right side of the TO) and high current (left side of the TO) parts.

To investigate the behavior of the $R500$ parameter, the resistance of the arc at the 500 ns instance prior to current interruption, the TO in the test circuit is replaced by the conductivity of Mayr's arc model (Equation (1)). From this equation, the corresponding arc resistance can be simply found by inverting the associated conductance at any time. Furthermore, without loss of generality, we assume the following default values for the optimization parameters: $P = 0.35$ MW, $\tau = 1$ μ s.

3. Results

The characteristics of the TRV waveform, such as the time delay of the transient recovery voltage (td), the rate of rise of the TRV (referred to as du/dt , and defined as the slope of TRV between 20% and 80% of its peak value), and the presence of parallel

capacitance (dubbed here as CLTG), influence arc–circuit interactions. In the following, the influence of these parameters, as well as that of Mayr's model arc parameters (P , τ), on the $R500$ threshold has been evaluated for each case individually.

3.1. Influence of Parallel Capacitance

The presence of an external capacitance, which is connected in parallel with the test object, helps current interruption during short line faults. This is because an extra capacitance slows down and delays the rise of the TRV. In addition, it takes away a portion of the current (i.e., $CLTG \cdot du/dt$) from the circuit breaker, effectively reducing the corresponding di/dt (just) before current zero. To investigate the influence of such phenomena on the $R500_{th}$, an extra capacitance (dubbed as CLTG) was placed in parallel to the TO in the test circuit shown in Figure 1.

The corresponding $R500$ values were then computed for different CLTG values, namely 0 nF, 4 nF, and 8 nF. To this end, the associated injected di/dt was swept. The results are represented in Figure 2, in which successful and failed operations have been marked in blue and red colors, respectively. As observed, in all three cases, there exists a threshold line ($R500_{th}$) separating failure and hold cases. Interestingly, it is observed that the threshold line is shifted down as CLTG increases. To visualize this trend better, the variation of $R500_{th}$ as a function of CLTG has been plotted in Figure 3. As observed, $R500_{th}$ decreases by a factor of 2.2 when CLTG is increased from zero to 10 nF. This result indicates that the threshold value for the $R500$ interruption criterion significantly changes with the presence of additional parallel capacitance.

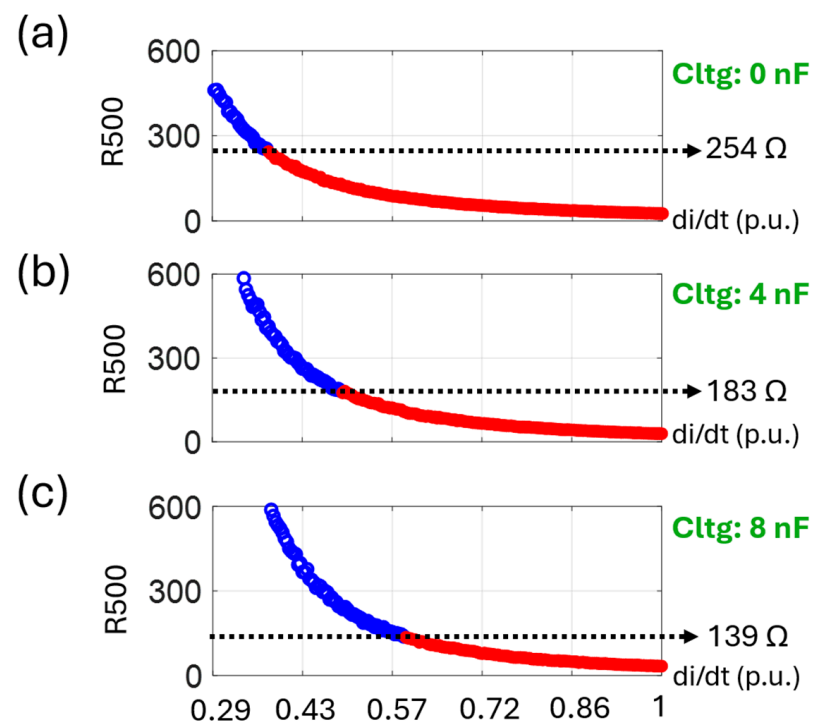


Figure 2. Influence of parallel capacitance on the $R500$ parameter. $R500$ values as a function of di/dt when $CLTG = 0$ (a), $CLTG = 4$ nF (b), and $CLTG = 8$ nF (c). Blue dots: successful operation, red dots: failed operations.

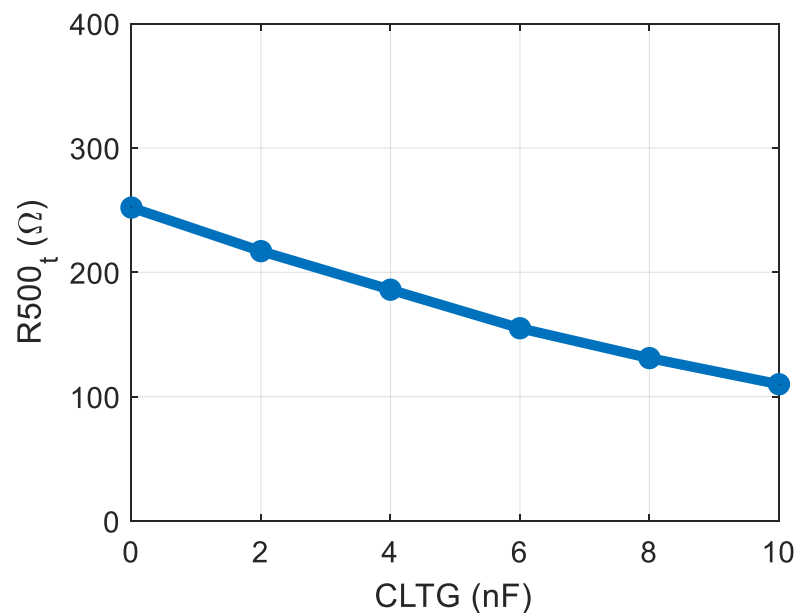


Figure 3. Influence of parallel capacitance on the threshold value for R500-based interruption criterion: $R500_{th}$ decreases as parallel capacitance (CLTG) increases.

3.2. Influence of Time Delay (td)

Another important factor influencing the thermal interruption process is the inherent time delay of the TRV waveform. A longer time delay of the TRV in the prospective shot eases the interruption process and reduces the risk of thermal runaway. In the previous section, it was shown that the presence of parallel capacitance can significantly influence $R500_{th}$. Considering the influence of the time delay of the TRV on the interruption process, one may naturally wonder whether the associated $R500_{th}$ is also affected by this parameter. To answer this question, the corresponding R500 values were computed for different time delays of the TRV waveform, namely 100 ns, 200 ns, and 500 ns. The corresponding results have been presented in Figure 4. Similar to the previous case, the exercise has been done by changing the injected di/dt . From the results of this figure, one deduces that the corresponding $R500_{th}$ is slightly reduced as td increases. To better illustrate this dependency, the evolution of $R500_{th}$ as a function of td is shown in Figure 5. It is seen that, by changing td from 100 ns to 500 ns, the associated $R500_{th}$ reduces by around 8%.

3.3. Influence of du/dt (Network Impedance)

Another important parameter influencing the interruption process is the number of interrupting units, which affects the corresponding voltage rate of rise (du/dt) or, equivalently, the effective impedance seen by each interrupter unit. Two or even more interrupting units (connected in series) helps thermal interruption by reducing the du/dt seen by each unit. The goal of this section is to evaluate whether this parameter has any influence on the $R500_{th}$. To this end, similar to previous cases, we plot the R500 values corresponding to different values of network impedance, namely Z_0 , $Z_0/2$, and $Z_0/4$, with $Z_0 = 450 \Omega$ being the characteristic impedance of the line in short line faults. Shown in Figure 6 is the R500 plots for these three cases, computed for different values of injected di/dt . As observed, the threshold value for the R500 method shifts down as the network impedance decreases. To show this trend more clearly, we plot in Figure 7 the $R500_{th}$ as a function of the network impedance. It is seen that $R500_{th}$ increases linearly with the increase of network impedance (or the associated du/dt). As such, one can also argue that $R500_{th}$ decreases linearly with the number of interrupting units.

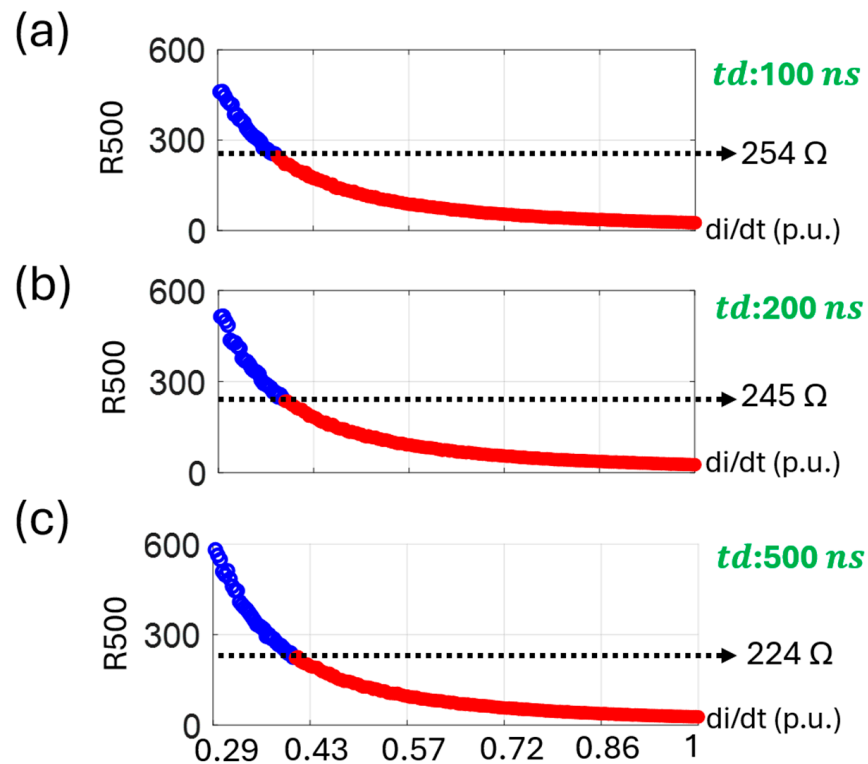


Figure 4. Influence of time delay of the TRV on the $R500$ parameter. $R500$ values as a function of di/dt when $td = 100\text{ ns}$ (a), $td = 200\text{ ns}$ (b), and $td = 500\text{ ns}$ (c). Blue dots: successful operation, red dots: failed operations.

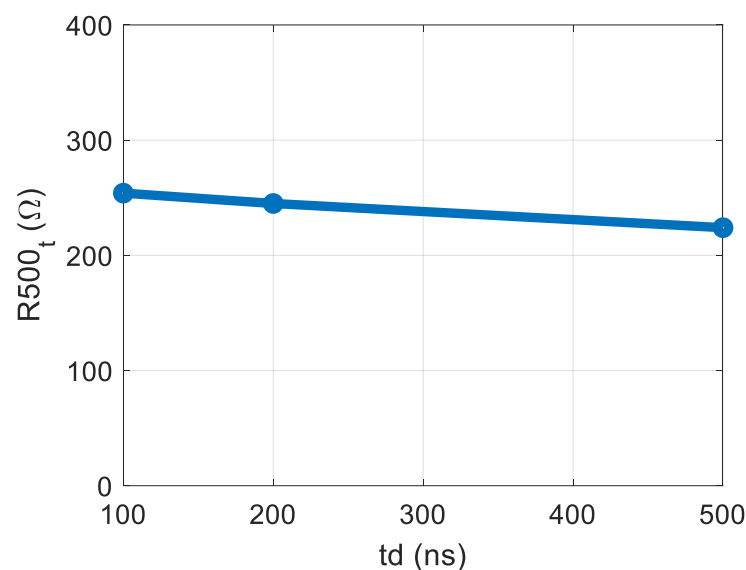


Figure 5. Influence of time delay of the TRV on the threshold value for $R500$ -based interruption criterion: $R500_{th}$ decreases as time delay (td) increases.

Until now, we have demonstrated how changing certain characteristics related to the circuit can influence $R500_{th}$. However, the following question has not been discussed: do the arc parameters used in Mayr's arc model have any influence on $R500_{th}$? In the following, we answer this question separately for the cooling power (P) and arc time constant (τ).

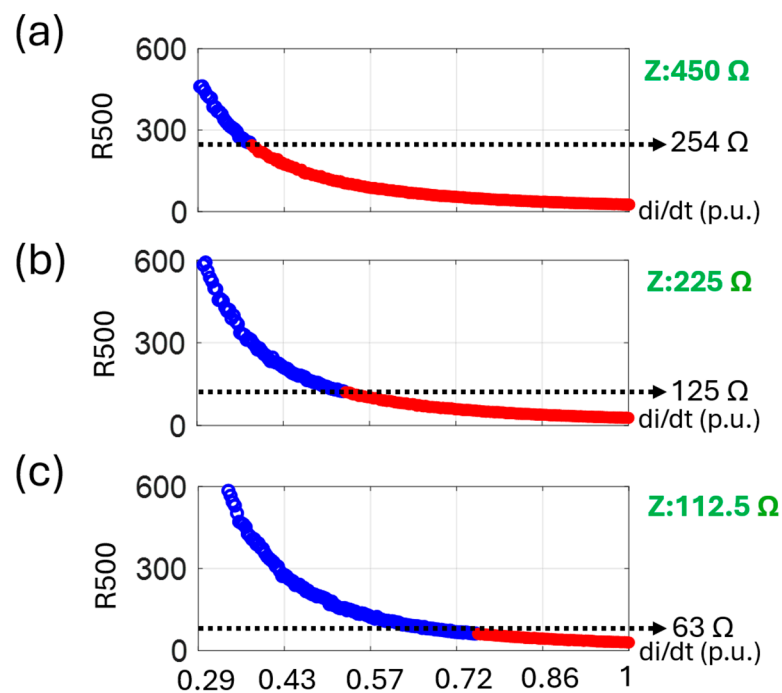


Figure 6. Influence of network impedance on the $R500$ parameter. $R500$ values as a function of di/dt when $Z = 450 \Omega$ (a), $Z = 225 \Omega$ (b), and $Z = 112.5 \Omega$ (c). Blue dots: successful operation, red dots: failed operations.

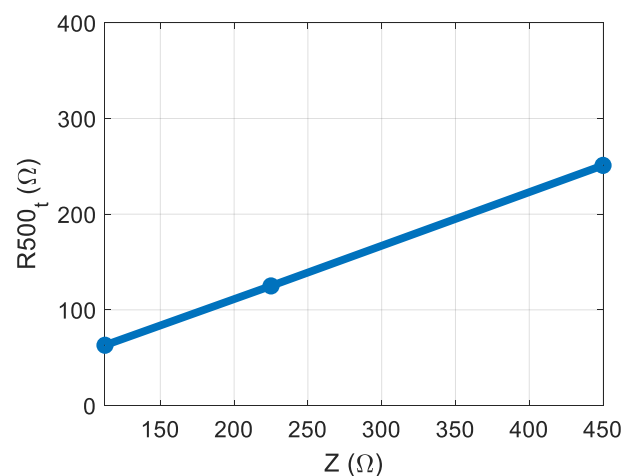


Figure 7. Influence of network impedance on the threshold value for $R500$ -based interruption criterion: $R500_{th}$ increases as network impedance (Z) increases.

3.4. Influence of Cooling Power (P)

To investigate the effect of cooling power, we compute $R500$ diagrams for three different choices of P , i.e., $P = 0.35$ MW, $P = 0.7$ MW, and $P = 1.4$ MW. The results have been represented in Figures 8 and 9. Note that these results have been obtained with $td = 100$ ns, $CLTG = 0$ nF, and $Z = 450 \Omega$. As seen in the figures, $R500_{th}$ has a very small dependency on the cooling power used in Mayr's model ($R500_{th}$ slightly decreases with increased cooling power). In fact, while doubling the cooling power increases the associated limit for di/dt by a factor of 2, it reduces the $R500_{th}$ by only 15%, which is typically hidden within the uncertainty of the measurements. This result is in line with previously published observations, based on empirical data, reporting a unique value for the $G200_{th}$ regardless of the design of the breaker and the rating [3].

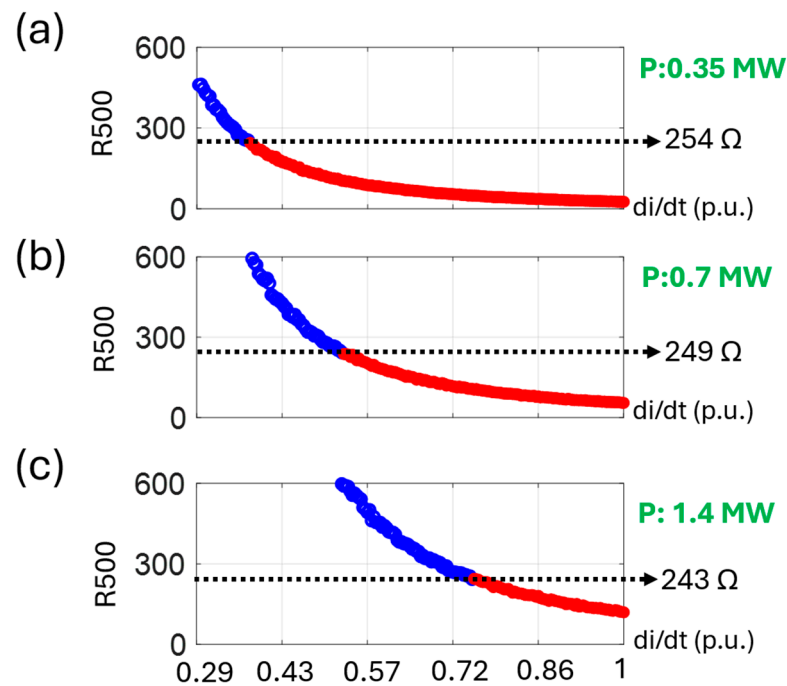


Figure 8. Influence of the cooling power on the $R500$ parameter. $R500$ values as a function of di/dt when $P = 0.35$ MW (a), $P = 0.7$ MW (b), and $P = 1.4$ MW (c). Blue dots: successful operation, red dots: failed operations.

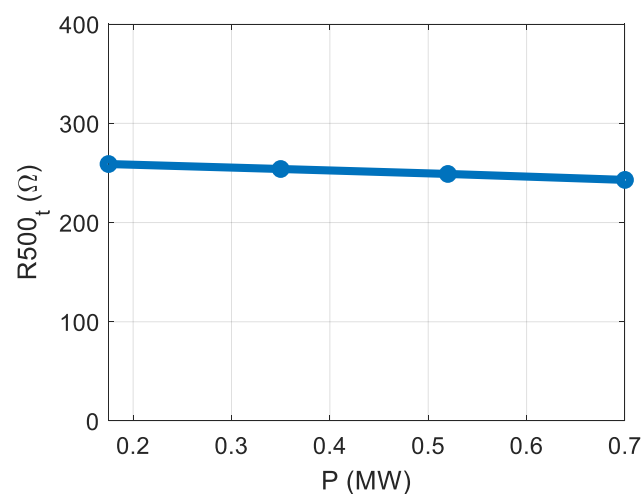


Figure 9. Influence of the cooling power on the threshold value for $R500$ -based interruption criterion: $R500_{th}$ slightly decreases as the cooling power of the breaker (P) increases.

It is worth mentioning that the exact timing at which the arc resistance is evaluated naturally influences the corresponding absolute value, as the resistance increases when approaching current zero. However, the relative variation of the arc resistance with changes in network parameters exhibits consistent behavior, regardless of the specific evaluation time. In other words, the exact same behavior was observed when we used $R200_{th}$ for evaluation.

3.5. Influence of Arc Time Constant (τ)

Apart from the cooling power P , the other optimization parameter used in Mayr's arc model is the arc time constant τ . The impact of this parameter on the $R500_{th}$ is the last analysis in the series. Figure 10 illustrates the computed $R500$ values for three different values of the arc time constant: $\tau = 1 \mu s$, $\tau = 1.5 \mu s$, and $\tau = 0.5 \mu s$.

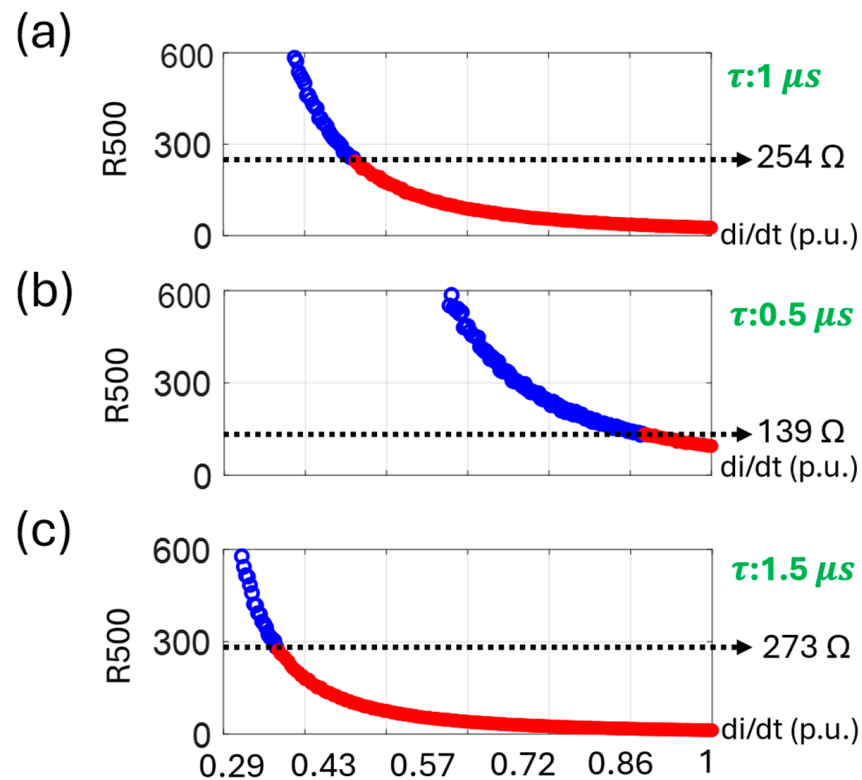


Figure 10. Influence of the arc time constant on the $R500$ parameter. $R500$ values as a function of di/dt when $\tau = 1 \mu s$ (a), $\tau = 0.5 \mu s$ (b), and $\tau = 1.5 \mu s$ (c). Blue dots: successful operation, red dots: failed operations.

As usual, the plots have been created by evaluating the $R500$ for swept values of di/dt . Interestingly, as opposed to the cooling power P , $R500_{th}$ exhibits a dependency on the arc time constant. More specifically, $R500_{th}$ increases by increasing the arc time constant τ , as clearly seen in Figure 11. This implies that gaseous mixtures with longer decision times increase the threshold limit for the $R500$ -based interruption limit criterion.

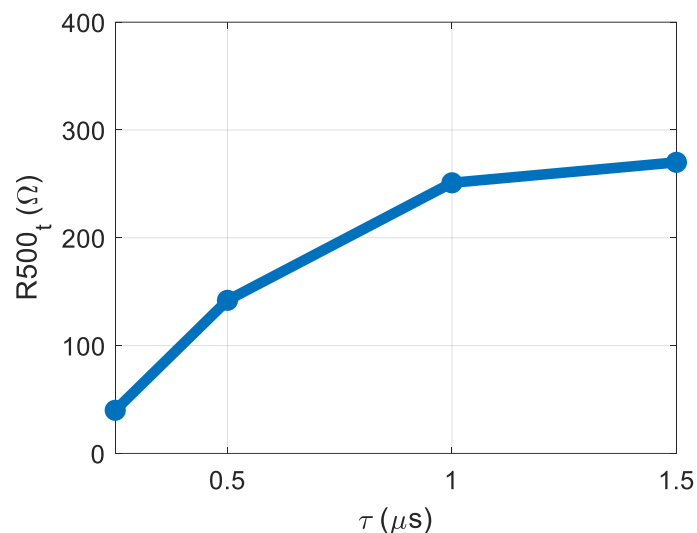


Figure 11. Influence of the arc time constant on the threshold value for $R500$ -based interruption criterion: $R500_{th}$ increases as the arc time constant (τ) increases.

3.6. Comparison with Empirical Data

Below we provide a detailed comparison between the simulation results and the empirical data reported in the literature. In [3], for SF₆-based interruption in HVCB, a threshold value of approximately 1 kΩ has been reported for the arc resistance measured at 200 ns before current zero. The interruption in such a gas is associated with an arc time constant of around $\tau = 0.4 \mu\text{s}$ [3]. For a CO₂-based gas mixture, on the other hand, the literature reports a higher threshold resistance in the range of 2–2.5 kΩ at the same time instant. Meanwhile, since the decision time for CO₂-based gas mixture is longer than that of the SF₆-based ones, they exhibit a larger arc time constant (in the range of $\tau = 1\text{--}1.2 \mu\text{s}$). Comparing the aforementioned values indicates that the associated threshold for the resistance increases by 100–150%, when changing the gas mixture from SF₆ to CO₂. Consistently, our simulation results, shown in Figure 11, indicate that the corresponding critical values also increase by 123% (from 117 Ω to 261 Ω), when changing the τ parameter from $\tau = 0.4 \mu\text{s}$ to $\tau = 1.2 \mu\text{s}$. Table 1 summarizes the values obtained from both Mayr's arc model simulations and experimental data. It should be noted that the absolute values of $R500_{th}$ obtained from the simulations are exactly equal to the empirical values, due to the simplicity of the underlying model. Yet, the empirical data summarized in this table confirms the simulated trends (in terms of relative shift of $R500_{th}$) with respect to variations in P and τ . For the remaining parameters, such as parallel capacitance and time delay, the influence is not validated experimentally in the present work and is therefore proposed as a subject for future investigation.

Table 1. Comparison between the empirical data [20] and Mayr model simulations.

	Empirical Data—R200	Mayr Model Simulations—R500
SF ₆ gas	1 kΩ	117Ω
CO ₂ -based gas	2–2.5 kΩ	261Ω
Relative change from SF ₆ to CO ₂	+100–150%	+123%

3.7. Influence of the Test Circuit Layout

The results presented above were derived using the special test circuit shown in Figure 1. As mentioned before, the adjustment of the di/dt was accomplished by tuning the charging voltage of the capacitor bank (C_{HV}). However, as already stated above, the variation of the charging voltage has a dual impact on interruption: in fact, it influences not only the di/dt but also the TRV. To isolate these two effects, we investigate the alternative testing scenario illustrated in Figure 12a. The test setup includes a source and a long transmission line, and the breaker in between (modeled with variable resistance controlled with Mayr's arc model equation with defined parameters P and τ and input signals current I and voltage V). A short circuit termination is applied to the end of the transmission line to mimic short circuit fault conditions. By adjusting the length of the transmission line, the corresponding di/dt (and du/dt) can be tuned. This modification, however, does not have any influence on the associated TRV peak as the length of the line is chosen to be sufficiently large. The corresponding behavior of the $R500_{th}$ parameter was then evaluated under a variation of the aforementioned arc and circuit characteristics.

The results of these investigations have been represented in Figure 12b. As observed, the results are in line with the previous ones. More specifically, it is observed that $R500_{th}$ is reduced by increasing the time delay and decreasing the network impedance (note that the curves correspond to different P , τ , and Z). However, it is significantly increased by increasing the arc time constant (τ).

Similar to the previous case, it is also observed that the sensitivity of $R500_{th}$ to this parameter is much more than that of the cooling power (P). However, the sensitivity of $R500_{th}$ to P is found to be a bit higher compared to the previous test circuit, since the TRV peak is not influenced in this case when the di/dt is increased. Overall, these findings confirm the earlier results. It is worth noting that the test circuit used for the analysis does not represent a realistic short line fault scenario. In fact, since the line length has been chosen to be sufficiently long, the corresponding TRV is more similar to a terminal fault test duty. This choice was made intentionally in order to exclude the effect of variations in the TRV peak. Such variations are caused by changes in the line length. More specifically, in realistic SLF scenarios with shorter lines, adjusting the line length to control the di/dt would simultaneously affect the associated TRV peak (which in turn also influences the threshold for $R500$, and this was not wanted in this case study).

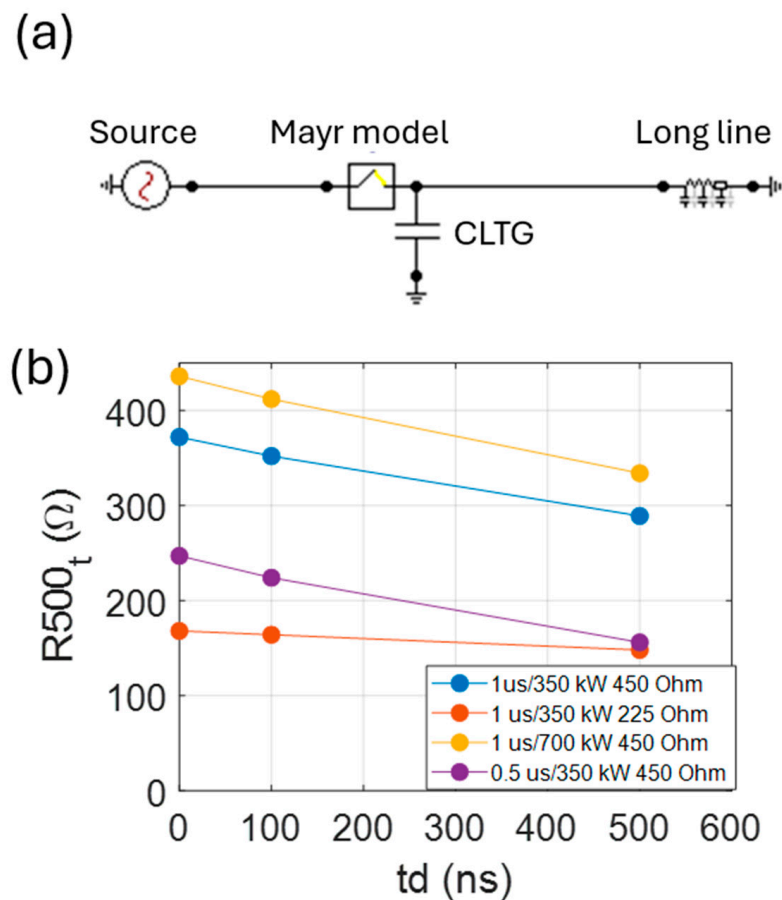


Figure 12. (a) Investigation of the $R500_{th}$ parameter in a different test setup, including a source, a long transmission line, and the breaker in between them, (b) $R500_{th}$ parameter as a function of the time delay for different arc (P , τ) and circuit parameters (Z , td).

3.8. Influence of the Arc Model on the Results

The results obtained so far were based on Mayr's arc model presented in Equation (1). At this stage, one may wonder if the chosen arc model has any influence on the $R500_{th}$ behavior. To address this question, we consider a more sophisticated and advanced black box arc model, including three conductance stages (G_1 , G_2 , G_3), each of which is described by a specific equation:

$$\frac{1}{G_1} \frac{dG_1}{dt} = \frac{1}{\tau_1} \left(\frac{I \cdot V}{P_1} - 1 \right) \quad (2)$$

$$\frac{1}{G_2} \frac{dG_2}{dt} = \frac{1}{\tau_2} \left(\frac{I \cdot V}{P_2 G_2^{0.6}} - 1 \right) \quad (3)$$

$$\frac{1}{G_3} \frac{dG_3}{dt} = \frac{1}{\tau_3} \left(\frac{I \cdot V}{P_3 G_2^{0.1}} - 1 \right) \quad (4)$$

where P_1 , P_2 , P_3 , τ_1 , τ_2 , and τ_3 are arc parameters. In the following, we assume that P_1 and τ_1 are constant and arbitrarily chosen ($P_1 = 0.35$ MW, $\tau_1 = 1$ μ s). Note that P_2 , P_3 , τ_2 , and τ_3 are defined according to [30]. Using this model, we investigated the influence of changing the network impedance on the corresponding $R500_{th}$. The results of this investigation have been shown in Figure 13. It is observed that $R500_{th}$ is reduced with decreasing network impedance, which represents the same qualitative trend as the results obtained based on the simple one stage model. The exercise was repeated to evaluate the influence of the time delay of the TRV on the $R500_{th}$. The results of this evaluation show the same qualitative trends as the ones obtained using the simple Mayr's arc model approach. Overall, it can be concluded that the drawn conclusions are not affected by the complexity of Mayr's arc model. In fact, similar conclusions are expected when even more sophisticated arc models (e.g., CFD-based) are employed for evaluating the arc conductance.

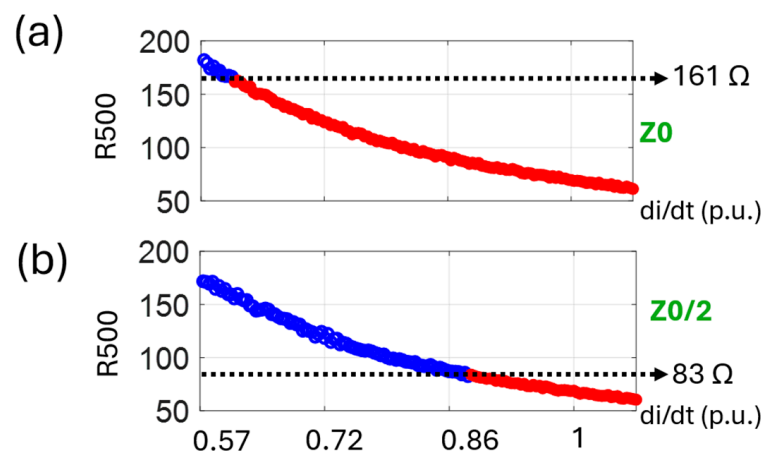


Figure 13. Investigation of the $R500_{th}$ parameter using the three-stage black box arc model, $R500$ values as a function of di/dt when $Z = 450 \, \Omega$ (a), $Z = 225 \, \Omega$ (b). Blue dots: successful operation, red dots: failed operations.

Finally, it is worth mentioning that the chosen cooling parameters for the three-stage Mayr's arc model do not correspond to a real circuit breaker but rather to a fictitious one. Nevertheless, the results obtained are not expected to be affected by the specific choice of cooling parameters. In other words, comparable results would be obtained using different cooling parameters, as already demonstrated with the simple one-stage Mayr's arc model.

As a specific example demonstrating that the choice of cooling parameters does not affect the overall behavior of the results, we again consider the simple one-stage model and the test circuit shown in Figure 1 and repeat the analysis of the influence of parallel capacitance on $R500_{th}$ parameter for a different set of arc parameters, namely $P = 0.7$ MW and $\tau = 1.2$ μ s. The corresponding results are summarized in Figure 14. As observed, these results exhibit very similar behavior to that obtained with the original values, i.e., $P = 0.35$ MW and $\tau = 1$ μ s. Of course, the absolute value of $R500_{th}$ varies with the selected model parameters; however, the overall trend and relative shift of $R500_{th}$ remains consistent.

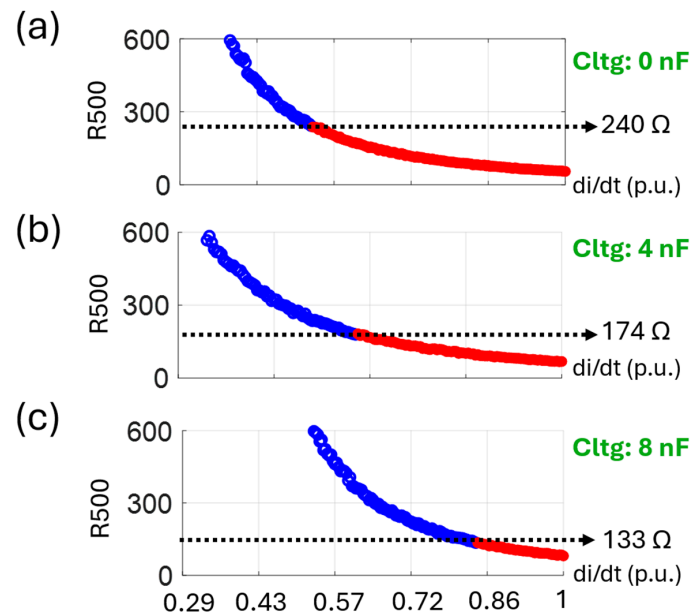


Figure 14. Influence of parallel capacitance on the $R500$ parameter for different values of arc parameters, namely $P = 0.7$ MW and $\tau = 1.2$ μ s. $R500$ values as a function of di/dt when $C_{LTG} = 0$ (a), $C_{LTG} = 4$ nF (b), and $C_{LTG} = 8$ nF (c). Blue dots: successful operation, red dots: failed operations.

3.9. Multi-Parameter Effect

So far, a single-parameter variation approach has been employed to isolate the physical influence of each parameter. In practical systems, however, multiple parameters may vary at the same time. Such cases lead to coupled effects, influencing the threshold value of the $R500$ for successful interruption. As an example, one may think of a scenario in which the number of interrupting units is doubled while an external parallel capacitance is simultaneously added in the test circuit to facilitate the interruption. In the following, we examine such a combined case with the previously described test setup shown in Figure 1.

To this end, we perform simulations for two different configurations. Case 1 corresponds to the reference scenario ($P = 0.35$ MW and $\tau = 1$ μ s) with a single interrupting unit and no additional parallel capacitance. Case 2 represents the modified scenario, in which the number of interrupting units is doubled and an additional parallel capacitance of 2 nF is connected across the breaker. Figure 15 compares the corresponding values of $R500_{th}$ for these two cases. As observed, $R500_{th}$ has decreased substantially in Case 2. Such a reduction is consistent with the fact that interruption is facilitated under these modifications.

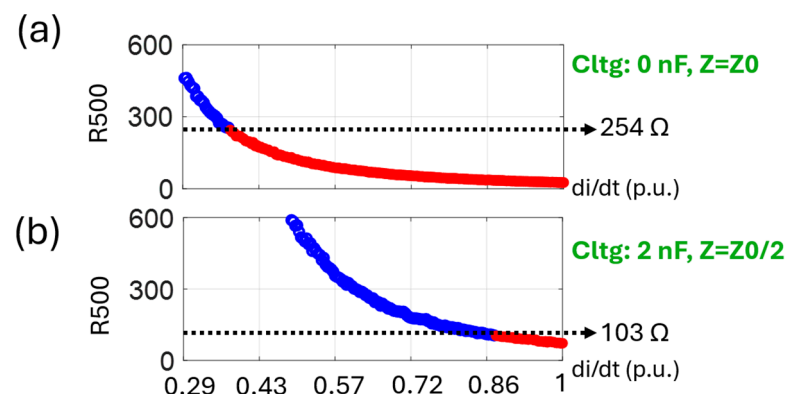


Figure 15. Influence of multi-parameter change on the $R500$ parameter. $R500$ values as a function of di/dt when $C_{LTG} = 0$, and $Z = Z_0 = 450$ Ω (a), $C_{LTG} = 2$ nF, and $Z = Z_0/2 = 225$ Ω (b). Blue dots: successful operation, red dots: failed operations.

4. Discussion

The main goal of this paper was to evaluate, based on Mayr's arc model, the influence of arc–circuit interaction on the threshold value $R500_{th}$ for the $R500$ -based interruption criterion method, according to which the interruption capability of the breaker increases as $R500_{th}$ decreases. It was demonstrated that certain parameters such as parallel capacitance, TRV time delay, and network impedance significantly influence the associated $R500_{th}$. In general, it was observed that larger values of parallel capacitance and TRV time delay led to a decrease of the required threshold limit for the $R500$ method. On the other hand, $R500_{th}$ rises by increasing the du/dt or, equivalently, the network impedance. The influence of Mayr's model arc parameters on the $R500_{th}$ were further investigated. While $R500_{th}$ did not exhibit significant dependency on the cooling power (P), it was greatly influenced by the arc time constant (τ). These observations were in line with previously published papers in the literature. Finally, it was shown that increasing the Mayr's arc model complexity by representing the arc as three resistors in series resulted in no change in the qualitative dependence of $R500_{th}$ on circuit and arc parameters, compared to the simple single-resistance model. The combined influence of circuit parameters on the $R500_{th}$ was further investigated and discussed. It was further demonstrated that, with appropriate calibration, the obtained numerical results can be translated into real world cases. However, it is worth mentioning that further research is needed to validate the model using additional test data from high-voltage circuit breakers. Expanding the analysis to include other arc models (e.g., Cassie–Mayr, CFD models), as well as investigating the impact of parameter combinations are other interesting topics for future research.

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Abbreviations

The following abbreviations are used in this manuscript:

HVCB	High-voltage circuit breaker
TRV	Transient recovery voltage
TO	Test object
HC	High current

References

1. Garzon, R.D. *High-Voltage Circuit Breakers: Design and Applications*; CRC Press: Boca Raton, FL, USA, 2002.
2. Seeger, M.; Smeets, R.; Yan, J.; Ito, H.; Claessens, M.; Dullni, E.; Falkingham, L.; Franck, C.M.; Gentils, F.; Hartmann, W.; et al. Recent trends in development of high-voltage circuit breakers with SF₆ alternative gases. *Plasma Phys. Technol.* **2017**, *4*, 8–12.
3. Kapetanovic, M. *High-Voltage Circuit Breakers*; ETF: Sarajevo, Bosnia and Herzegovina, 2011.
4. Nakanishi, K. *Switching Phenomena in High-Voltage Circuit Breakers*; Routledge: London, UK, 2017.
5. Ziani, A.; Moulai, H. Extinction properties of electric arcs in high-voltage circuit breakers. *J. Phys. D Appl. Phys.* **2009**, *42*, 105205.

6. Guo, Z.; Liu, S.; Pu, Y.; Zhang, B.; Li, X.; Tang, F.; Lv, Q.; Jia, S. Study of the arc interruption performance of CO₂ gas in high-voltage circuit breaker. *IEEE Trans. Plasma Sci.* **2019**, *47*, 2742–2751. [\[CrossRef\]](#)
7. Budin, A.V.; Pinchuk, M.E.; Kuznetsov, V.E.; Leont'EV, V.V.; Kurakina, N.K. An experimental setup for investigation of arc and erosion processes in high-voltage high-current breakers. *Instrum. Exp. Tech.* **2017**, *60*, 837–842.
8. Zhou, Y.; Humphries, J.; Spencer, J.; Yan, J. Experimental study of arc erosion in gas-blasting and free-burning conditions in high-voltage circuit breakers. *Plasma Phys. Technol.* **2023**, *10*, 32–35.
9. Ye, X.; Dhotre, M.T.; Mantilla, J.D.; Kotilainen, S. CFD analysis of the thermal interruption process of gases with low environmental impact in high-voltage circuit breakers. In *Proceedings of the 2015 IEEE Electrical Insulation Conference (EIC)*; IEEE: New York, NY, USA, 2015.
10. Ito, H.; Dufournet, D. Interrupting Phenomena of High-Voltage Circuit Breaker. In *Switching Equipment*; Springer: Cham, Switzerland, 2019; pp. 63–81.
11. Sakuyama, T.; Kotsuji, H.; Terada, M.; Shiraishi, K.; Urai, H. Interrupter Size Effect of High-Voltage Gas Circuit Breaker on Thermal Interruption Performance and Current Zero Properties. *IEEJ Trans. Electr. Electron. Eng.* **2021**, *16*, 215–225. [\[CrossRef\]](#)
12. Seeger, M.; Galletti, B.; Bini, R.; Dousset, V.; Iordanidis, A.; Over, D.; Mahdizadeh, N.; Schwinne, M.; Stoller, P.; Votteler, T. Some aspects of current interruption physics in high-voltage circuit breakers. *Contrib. Plasma Phys.* **2014**, *54*, 225–234. [\[CrossRef\]](#)
13. Nikolic, P.G.; Schnettler, A. Investigations on the influence of the switching chamber design on the thermal interruption performance of carbon dioxide in high-voltage circuit breakers. In *Proceedings of the 2014 IEEE International Power Modulator and High-Voltage Conference (IPMHVC)*; IEEE: New York, NY, USA, 2014.
14. Oh, Y.; Lee, H.J.; Song, K.-D.; Kim, J.-K.; Hahn, S.-C. Predicting Thermal Interruption Characteristics of a 72.5-kV CO₂ Circuit Breaker. *IEEE Trans. Plasma Sci.* **2018**, *46*, 982–989. [\[CrossRef\]](#)
15. Zou, H.; Xu, B.; Wei, J.; Peng, Z.; Lin, X. Dynamic Characteristics Analysis of 550 kV Fast Circuit Breaker Repulsion Valve. In *Proceedings of the 2024 7th International Conference on Electric Power Equipment-Switching Technology (ICEPE-ST)*; IEEE: New York, NY, USA, 2024.
16. Huang, S.; Zhou, Y.; Xiong, L.; Dong, Z.Y.; Huang, W.; Gao, F.; Zhou, Q.; Li, X.; Zhu, L.; Li, Y. Resilient Distributed Observer-Based Fault-Tolerant Control for Islanded AC Microgrids Subject to Actuator Fault and Saturation Constraints. *IEEE Trans. Consum. Electron.* **2026**, *72*, 2787–2801. [\[CrossRef\]](#)
17. Yin, S.; Dong, E.; Tian, Y.; Feng, X.; Zhang, L.; Xie, K.; Ma, Z. Time Scatter Analysis of 800kV Fast Circuit Breaker. In *Proceedings of the 2024 7th International Conference on Electric Power Equipment-Switching Technology (ICEPE-ST)*; IEEE: New York, NY, USA, 2024.
18. Knobloch, H.; Habedank, U. Arc resistance at current zero: A tool to describe the breaking capacity of SF₆/sub 6/circuit-breakers at short-line faults. In *Eleventh International Symposium on High-Voltage Engineering*; IET: London, UK, 1999; Volume 3.
19. Tanaka, Y.; Nakano, T.; Hao, S.; Tomita, K.; Inada, Y.; Kumada, A.; Hidaka, K.; Fujino, T.; Suzuki, K.; Shinkai, T. Fundamental studies on switching arcs—Experimental and numerical approaches. In *Proceedings of the 2017 4th International Conference on Electric Power Equipment-Switching Technology (ICEPE-ST)*; IEEE: New York, NY, USA, 2017.
20. Pietrzak, P.; Muratović, M.; Seeger, M.; Engelbrecht, J.; Votteler, T. Arc conductance decay as a performance indicator for thermal interruption in CO₂/O₂ mixture. *Plasma Phys. Technol.* **2025**, *12*, 214–218. [\[CrossRef\]](#)
21. Liu, K.; Li, B.; Jiang, Q.; Zhang, Y.; Liu, T. Fault ride-through strategy for hybrid cascaded HVDC systems based on controllable LCC. *IEEE Trans. Circuits Syst. II Express Briefs* **2025**, *73*, 88–92. [\[CrossRef\]](#)
22. Gustavsson, N. *Evaluation and Simulation of Black-Box Arc Models for High-Voltage Circuit-Breakers*; Linköping University: Linköping, Sweden, 2004.
23. Smeets, R.P.; Kertesz, V. Evaluation of high-voltage circuit breaker performance with a new validated arc model. *IEE Proc.-Gener. Transm. Distrib.* **2000**, *147*, 121–125. [\[CrossRef\]](#)
24. Nejad, F.Z.; Galletti, B.; Votteler, T.; Kumar, S. Application of the Mayr Arc Model for Characterizing the Interruption Performance of CO₂-Based High-Voltage Circuit Breakers. In *Proceedings of the 2024 7th International Conference on Electric Power Equipment-Switching Technology (ICEPE-ST)*; IEEE: New York, NY, USA, 2024.
25. Gouda, O.; Ibrahim, D.K.; Soliman, A. Parameters affecting the arcing time of HVDC circuit breakers using black box arc model. *IET Gener. Transm. Distrib.* **2019**, *13*, 461–467. [\[CrossRef\]](#)
26. Udagawa, K.; Koshizuka, T.; Uchii, T.; Shinkai, T.; Kawano, H. CO₂ circuit Breaker arc model for EMTP Simulation of SLF Interrupting Performance. *Int. Electro Tech. Comm.* **2011**, 62271, 100.
27. Walter, M.; Franck, C. Improved method for direct black-box arc parameter determination and model validation. *IEEE Trans. Power Deliv.* **2014**, *29*, 580–588. [\[CrossRef\]](#)
28. Smeets, R.; Kertész, V.; Nishiwaki, S.; Suzuki, K. Performance evaluation of high-voltage circuit breakers by means of current zero analysis. In *IEEE/PES Transmission and Distribution Conference and Exhibition*; IEEE: New York, NY, USA, 2002; Volume 1.
29. Golestani, S.; Samet, H. Generalised Cassie–Mayr electric arc furnace models. *IET Gener. Transm. Distrib.* **2016**, *10*, 3364–3373. [\[CrossRef\]](#)

30. Ohtaka, T.; Kertész, V.; Smeets, R. Novel black-box arc model validated by high-voltage circuit breaker testing. *IEEE Trans. Power Deliv.* **2017**, *33*, 1835–1844.
31. Park, K.; Usman, M.; Lee, B. Optimization of the Black-Box Arc Models for DC Current Limiting Circuit Breakers Using Levenberg-Marquardt Algorithm. *IEEE Access* **2023**, *11*, 127334–127347.
32. Mayr, O. Beitrage zur Theorie des Statischen und des Dynamischen Lichthogens. *Arch. Für Elektrotech.* **1943**, *37*, 588–608. [[CrossRef](#)]

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