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SF_6-alternative 145 kV live-tank circuit breaker

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SUMMARY

The development of a 145 kV / 40 kA / 3150 A / 50 Hz live-tank high voltage circuit breaker product that uses a mixture of CO_2 and O_2 as an alternative to SF_6 as the current interruption and dielectric insulation medium is described. The key changes to the design of the arc zone made to improve performance for the new gas mixture are presented. CO_2 - O_2 mixtures differ from SF_6 in their thermodynamic and transport properties, for example, in their speed of sound and in their adiabatic coefficient. Computational fluid dynamics of the gas flow, including a model of the arc, and finite element method simulations of the electric field distribution were used to refine and select proper designs. The circuit breaker successfully passed all the type tests required according to the IEC 62271-100 standards. The design changes relevant for achieving good performance are often specific to a certain type test. The dielectric design was improved to address the capacitive switching requirements. The performance for low short-circuit currents was addressed by ensuring sufficient gas flow at lower arcing times and compensating for the higher speed of sound of CO_2 compared to SF_6. The mechanical robustness of the circuit breaker was improved through several minor changes, yielding performance in the T100a test, where maximum arc energy is input, that exceeds the requirements of the IEC standard. The gas in the circuit breaker was analyzed after this test, and separate tests with the same gas mixture were performed on a circuit-breaker-based laboratory test device. The gas analysis, together with a toxicity assessment, shows that even after exposure to an arc energy input corresponding to many short-circuit current interruptions, the gas mixture is not classified as toxic according to the Globally Harmonized System of Classification and Labeling of Chemicals.

KEYWORDS

Circuit breaker, carbon dioxide, oxygen, SF_6-alternative, high voltage, live tank, current interruption.

INTRODUCTION

Live-tank circuit breakers have long used SF_6 as the insulating and current interrupting medium. The high dielectric strength and current interrupting performance of SF_6 permit the design of compact, cost-effective, and reliable circuit breakers that address the short-circuit current and voltage requirements of electric power transmission and distribution networks. Furthermore, SF_6 is chemically stable, is non-toxic and has an ozone depletion potential of zero. However, SF_6 has a high greenhouse warming potential of 23500 (in terms of CO_2-equivalent) [1].

Mixtures of CO_2 and O_2 represent a promising alternative to SF_6 as the insulating and current interrupting medium in high voltage equipment and have been extensively investigated in recent years [2][3][4]. Live-tank circuit breaker products using CO_2 / O_2 mixtures are available and successfully installed in the field for voltages up to 145 kV [5][6]. While the dielectric strength of CO_2 / O_2 mixtures does not reach that of SF_6, increasing the gas filling pressure can at least partially compensate the lower intrinsic performance [4][7][8]. CO_2 / O_2 mixtures can also be used as the background gas for mixtures that include relatively low concentrations of a high-boiling-point additive with high dielectric strength [9]. However, CO_2 / O_2 mixtures by themselves have good switching performance and can be used down to the lowest specified minimum operating temperatures for electrical equipment due to the low boiling point of CO_2 [4].

Many of the reliable and proven design concepts used in SF_6 live-tank circuit breakers, which were developed, refined, and tested in the real world for decades, translate directly to CO_2 / O_2 circuit breakers. However, the thermodynamic properties of CO_2 / O_2 mixtures differ significantly from those of SF_6 [4]. A benchmark comparison of a CO_2 / O_2 mixture and an SF_6 mixture in a circuit breaker design optimized for SF_6 can be misleading—it will suggest a lower CO_2 / O_2 performance than can actually be achieved in a circuit breaker designed specifically for CO_2 / O_2 [10]. Performance improvements can be achieved by adapting the arc zone, including the contacts, the nozzles, and the intermediate volumes where gas is compressed and temporarily stored during the interruption process, to the CO_2 / O_2 gas mixture. The higher speed of sound and adiabatic coefficient of CO_2 / O_2 mixtures compared to SF_6 leads, for example, to higher pressure build-up in self-blast circuit breakers (where the arc energy itself is used to help blow and extinguish the arc) and to faster outflow speeds [4]. A good design can use these properties of CO_2 / O_2 mixtures to effectively cool and extinguish the arc.

In this paper we show how relatively small changes to the arc zone of a circuit breaker can be used to achieve high current-interruption performance with a CO_2 / O_2 gas mixture. We focus on a 145 kV / 40 kA / 50 Hz live-tank circuit breaker. We describe the performance of the resulting circuit breaker in development- and type-tests performed according to the IEC 62271-100 and IEC 62271-101 standards. We also present measurements of the gaseous decomposition products that can form in small amounts when CO_2 is exposed to a short-circuit current arc and show that they do not compromise performance or safety of the equipment.

ARC ZONE MODIFICATIONS TO IMPROVE PERFORMANCE WITH CO_2 / O_2

SF_6 circuit breakers have been optimized over decades to achieve reliable performance under many different conditions in the power grid, and development of CO_2 / O_2 circuit breakers can take advantage of this research and knowledge. We demonstrate that small changes in and around the arc zone can be used to improve current interruption performance across the full range of different short-circuit interruption and switching duties.

The cold dielectric strength of an insulating gas is a key parameter in designing a circuit breaker, and CO_2 / O_2 has an intrinsically lower dielectric strength than SF_6 [7][8]. To address this, the filling pressure of the gas is increased, since the breakdown field strength increases with molecule number density. Furthermore, the gap between the contacts in the fully open position is increased, and the speed at which the contacts open is also increased. An increase in speed generally comes at the cost of increased drive energy. However, a double-move design, where both contacts are moved (including the lighter contact) can be used to achieve higher speeds more efficiently. The metal shields surrounding the nominal contacts and the arcing contacts of the circuit breaker are also adjusted to reduce the field stress and to adapt them to the increased contact gap.

The CO_2 / O_2 circuit breaker is based on the self-blast principle, which makes use of the arc energy itself to help cool and extinguish the arc. A schematic of a self-blast circuit breaker is presented in Figure 1. During the high current phase of arcing (one or two power frequency half-waves before the current is interrupted at a zero-crossing), the arc ablates polytetrafluoroethylene (PTFE) from the nozzles, leading to a pressure build-up in an upstream self-blast volume. This self-blast volume is connected to a compression volume, where the gas is compressed mechanically by the operation of the circuit breaker, by a valve. For high short-circuit currents (corresponding to T60 test duties or higher, as defined in the IEC 62271-100 standard), this valve is closed during the high current phase, since the pressure generated by the arc-ablated PTFE in the self-blast volume is higher than the mechanically generated pressure in the compression volume. However, for lower currents (typically corresponding to T30 short-circuit test duties or lower), this valve will be open during at least a significant part of the current interruption process. In this case, mechanically compressed gas from the compression volume plays a role in cooling and extinguishing the arc. Due to its higher speed of sound compared to SF_6, CO_2 can flow out of the compression volume faster once the arcing contacts have opened, leading to a more rapid drop in pressure [4]. The compression volume can be increased in size to compensate for the faster outflow of CO_2, thereby ensuring that sufficient gas flow is present long enough to cool the arc zone after a zero-crossing, even for long arcing times (where the contacts open, and gas flow starts early relative to the zero-crossing).

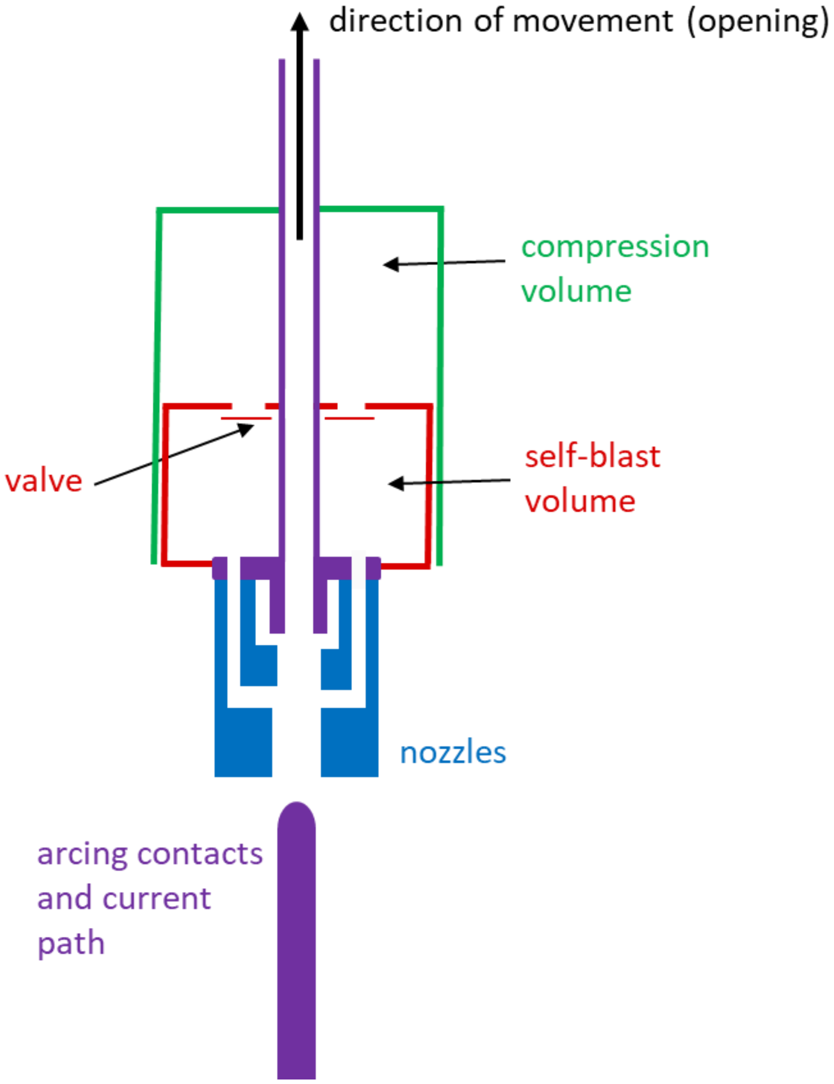

Figure 1. Schematic diagram of a cross-section through the arc zone and its immediate vicinity of a self-blast circuit breaker.

SIMULATIONS AND FEM ANALYSIS

An important step in developing the circuit breaker was dimensioning and ensuring proper distribution of the electrical field in and around the arc zone, including the arcing contacts and the nominal contacts. Finite element method calculations were performed to calculate the electric field distribution. The contact gap, the contact design, and the design of the surrounding shields were optimized with the help of these calculations. Specifically, these calculations permitted reduction of the electric field stresses in the CO_2 circuit breaker compared to an SF_6 circuit breaker. The final design had similar dielectric margins to the margins achieved in well-designed SF_6 circuit breakers. Refer to Figure 2 for an example of an electric field calculation for a prototype circuit breaker.

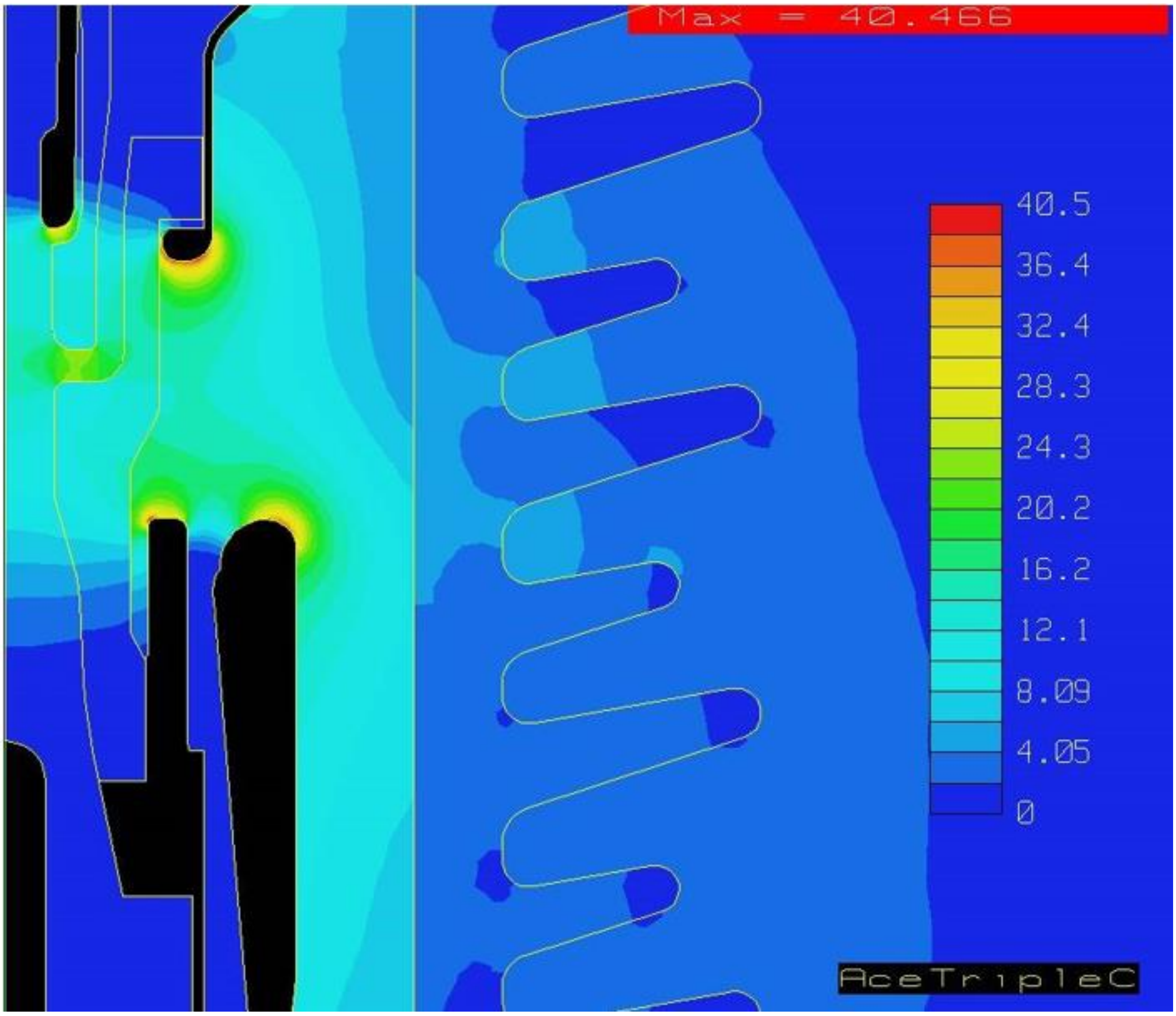

Figure 2. Electric field calculation in and around the arc zone of a live-tank circuit breaker.

A full dynamic calculation of the circuit breaker was performed. Computational fluid dynamics (CFD) simulations that take into account arc physics and the gas flow inside the circuit breaker were coupled with mechanical simulations and used to optimize the design of the circuit breaker. This coupling permitted accurate simulation of the contact speed and the compression of the gas for different test duties and taking into account the properties of the opening and closing springs of the drive. The model is illustrated in Figure 3. The result of a computational fluid dynamics calculation (encompassing the arc zone and its immediate surroundings) is illustrated in Figure 4. The simulations enabled a reduction in the energy required for operation of the circuit breaker and permitted construction of a light circuit breaker, with a size and footprint identical to that of SF_6 circuit breakers designed for the same system voltage.

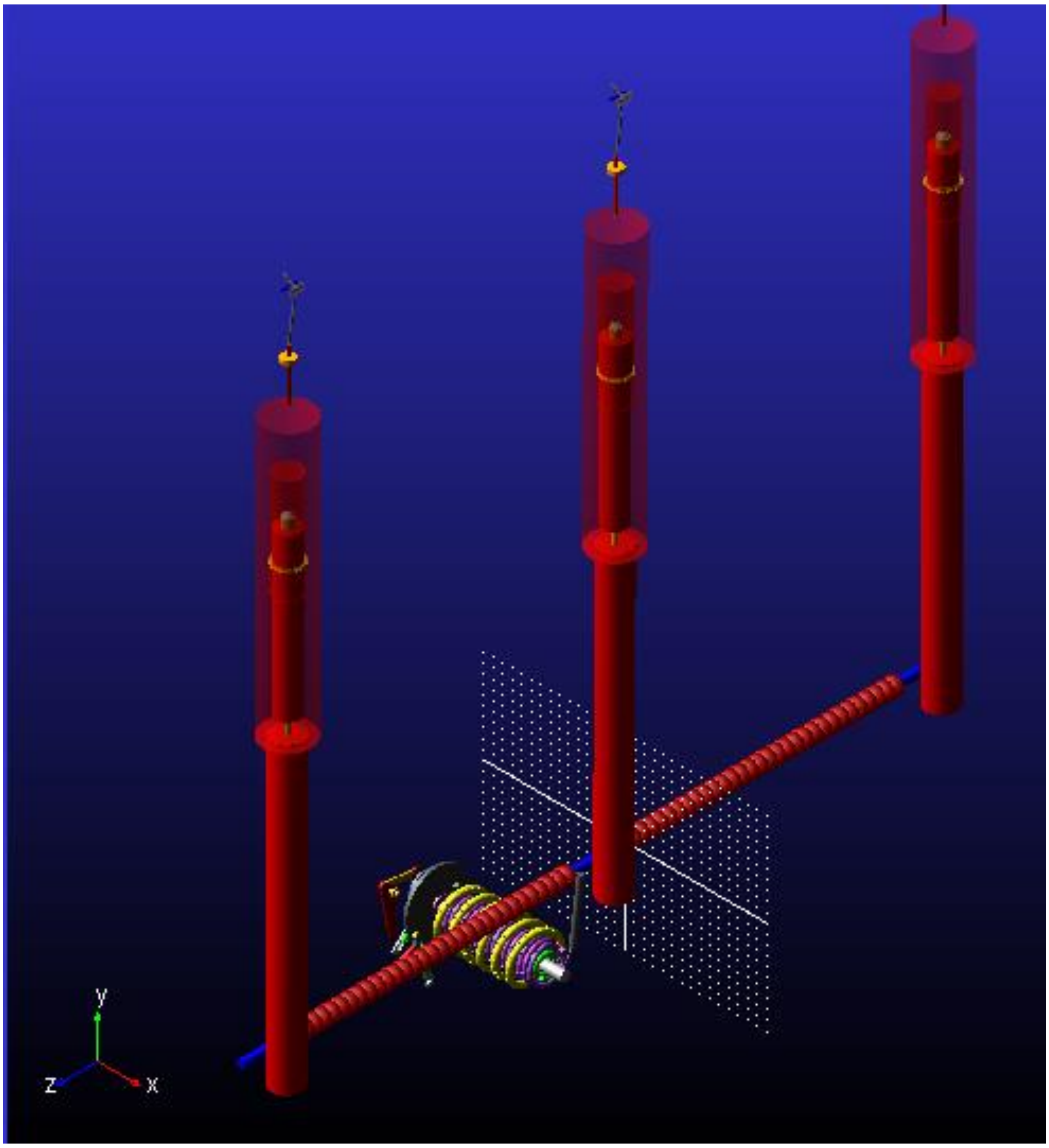

Figure 3. Illustration of the model used to simulate and optimize the performance of the circuit breaker.

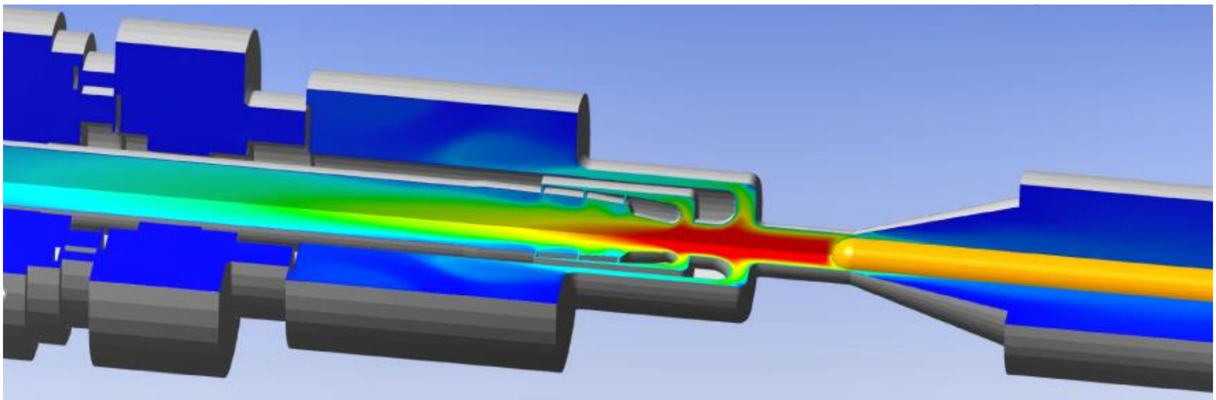

Figure 4. Temperature distribution calculated in the arc zone of a circuit breaker during interruption of a short-circuit current. The result illustrates conditions in the arc zone during the high current phase, when hot gas from the arc zone flows into the self-blast volume.

DEVELOPMENT AND TYPE TESTING

The 145 kV live-tank circuit breaker passed all type tests required by the IEC 62271-100 standards and was successfully launched as a product and installed at sites in several countries. An example of such an installation is shown in Figure 5. The circuit breaker has a nominal current rating of 3150 A (50 Hz) and a short-circuit current rating of 40 kA (50 Hz). Due to the very low boiling point of CO_2, the circuit breaker can be used even in extremely cold climates; it has a minimum operating temperature of −50 °C. Since several changes were made to the circuit breaker design to optimize it for CO_2, significant effort was also devoted to ensuring that these changes in no way compromised mechanical performance. In fact, the circuit breaker successfully passed the class M2 mechanical type test.

Figure 5. Photograph of the 145 kV, 3150 A (nominal), 40 kA (short-circuit), 50 Hz circuit breaker installed in a substation in Europe.

Circuit breakers are required to rapidly interrupt the current and withstand the voltage that rises across them afterwards under a wide range of different network conditions, ranging from a short-circuit fault with maximum current flow, to short-circuit faults with lower current flow (but typically also a steeper rise of the transient recovery voltage), to switching of resistive and capacitive loads under normal operating conditions of the power gid.

The capacitive switching, T10, and T100a are representative test duties and adaptations to the arc zone to improve performance for CO_2 / O_2 mixtures were required to ensure robust circuit breaker performance, as already discussed above. Clearly, other test duties are also important, but for simplicity we focus on the three mentioned duties. We show how the relevant design changes are connected to the differences in thermodynamic properties between CO_2 / O_2 mixtures and SF_6.

Capacitive switching (for example, switching unloaded overhead transmission lines or cables) is an important test duty for a circuit breaker. Capacitive currents are typically small and readily interrupted by the circuit breaker, resulting in very short minimum arcing times. Due to the low current that flowed, cold gas in the arc zone can rapidly be replenished from the self-blast and compression volumes. The voltage subsequently rising across the circuit breaker can exceed 2 p.u., since the disconnected line, cable, or capacitor bank retains its charge (and voltage), while the network voltage swings to the opposite polarity within half a period of the power frequency (50 Hz or 60 Hz). To avoid breakdown in the cold gas, the contacts must separate sufficiently quickly during this voltage rise. To address the capacitive switching requirement, a double-move concept (both arcing contacts are moved by the drive) was implemented, the shields surrounding the contacts were modified to optimize the electric field distribution, and the relative speed of the contacts was selected to be sufficiently fast.

As already mentioned above, the size of the compression volume was increased, providing more gas and a longer phase with sufficiently high mechanical blowing pressure to interrupt the arc under conditions with low short-circuit currents (such as the T10 or out-of-phase test duties). Previous studies have shown that the current interruption performance is linked to the blowing pressure [12].

Finally, changes were also made to address the T100a test duty (rated symmetric short-circuit current and maximum asymmetric component), the test duty with the maximum energy input into the circuit breaker. Differences in the adiabatic coefficient between CO_2 and SF_6 lead to higher temperatures and pressures in CO_2-based circuit breakers, particularly in the arc zone and its surroundings, including the self-blast volume. By improving the robustness of the circuit breaker and mechanically re-enforcing certain critical locations, the T100a performance was improved to the point where it exceeded the requirements of the IEC standard: Ten full T100a operations could successfully be performed on a single interrupting chamber.

RE-COMBINATION OF THE ARCING MEDIUM

As is the case for SF_6, almost all the CO_2 and O_2 molecules that are decomposed to atoms and ions in a high temperature arc recombine once the gas cools. The presence of O_2 helps to ensure that CO_2 recombines completely, and thereby CO and solid carbon (soot) formation can be minimized. However, some decomposition products do form in low concentrations. To address this topic and provide quantitative information, a study was performed in a circuit breaker test device under laboratory conditions. The test device, which had a volume of 60 L and was based on a high voltage live-tank circuit breaker, is described in more detail in [11], together with the equipment and procedure used for gas sampling. Briefly, the test device was exposed to approximately fifteen short-circuit current interruption operations; each operation input roughly 100 kJ into the circuit breaker. After every few operations, a gas sample was acquired. The increase in concentration of the decomposition product could thus be monitored during the test.

The gas samples were analyzed using gas chromatography – mass spectrometry and Fourier transform infrared spectroscopy. The following decomposition products were found: CO, CF_4, and COF_2 (in very low concentrations, below the quantification threshold). The change in CO concentration is illustrated in Figure 6 as a function of the input energy (normalized to the volume).

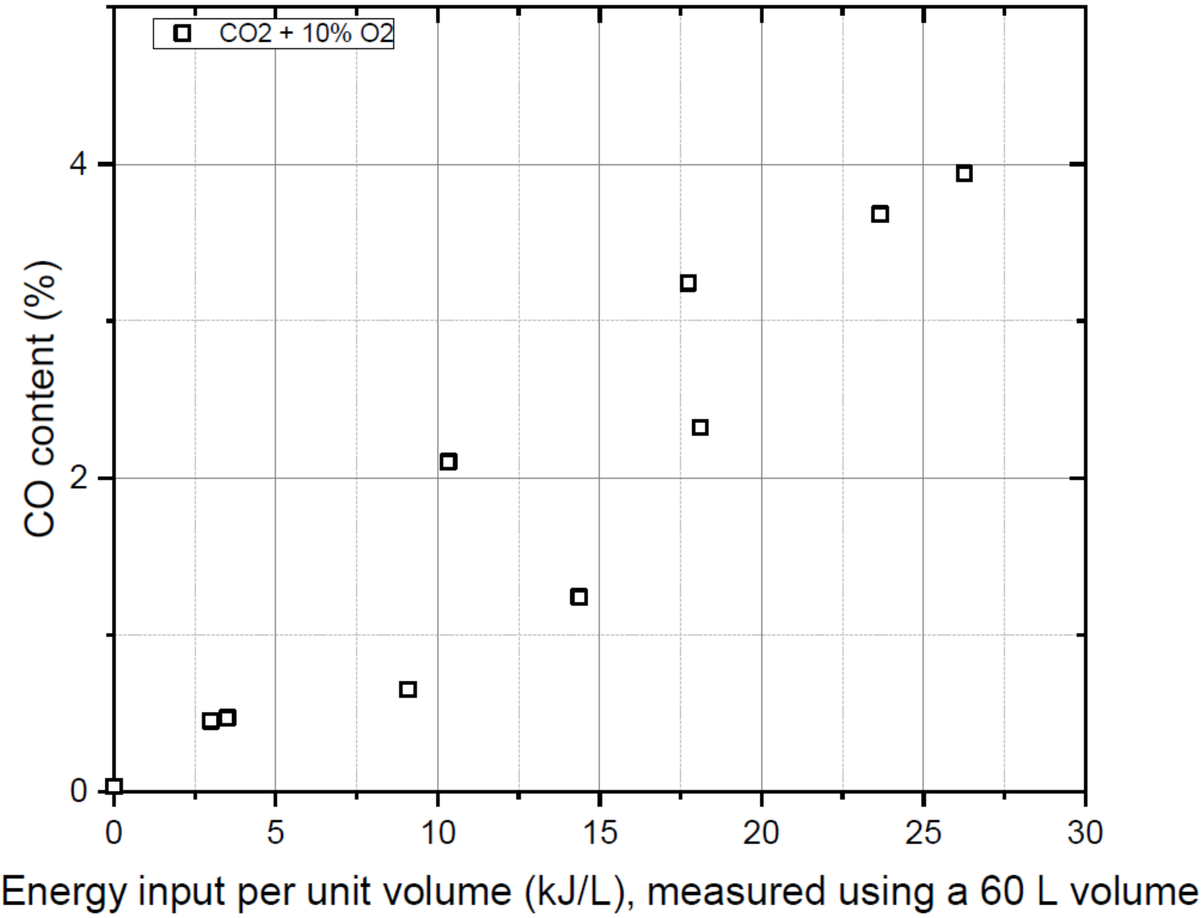

Figure 6. Carbon monoxide concentration in a live-tank circuit breaker-based test device, plotted as a function of the arc energy input (normalized to the 60 L volume of the test device).

The acute toxicity, which is often quantified as the concentration at which 50 % of the subjects in an animal test die for an exposure time of four hours (4-hour LC_{50}), can be calculated for the arc-exposed gas mixture. The concentration as a function of input energy (normalized to the volume) is shown in Figure 7. According to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), a gas mixture with a 4-hour LC_{50} of > 20,000 ppmv is not classified; this level is indicated by a horizontal red line in the plot. It should be noted that the higher the 4-hour LC_{50}, the higher the required concentration of a substance (or mixture of substances) needed for it to be toxic. Thus, a higher 4-hour LC_{50} corresponds to a lower toxicity and a lower 4-hour LC50 corresponds to a higher toxicity.

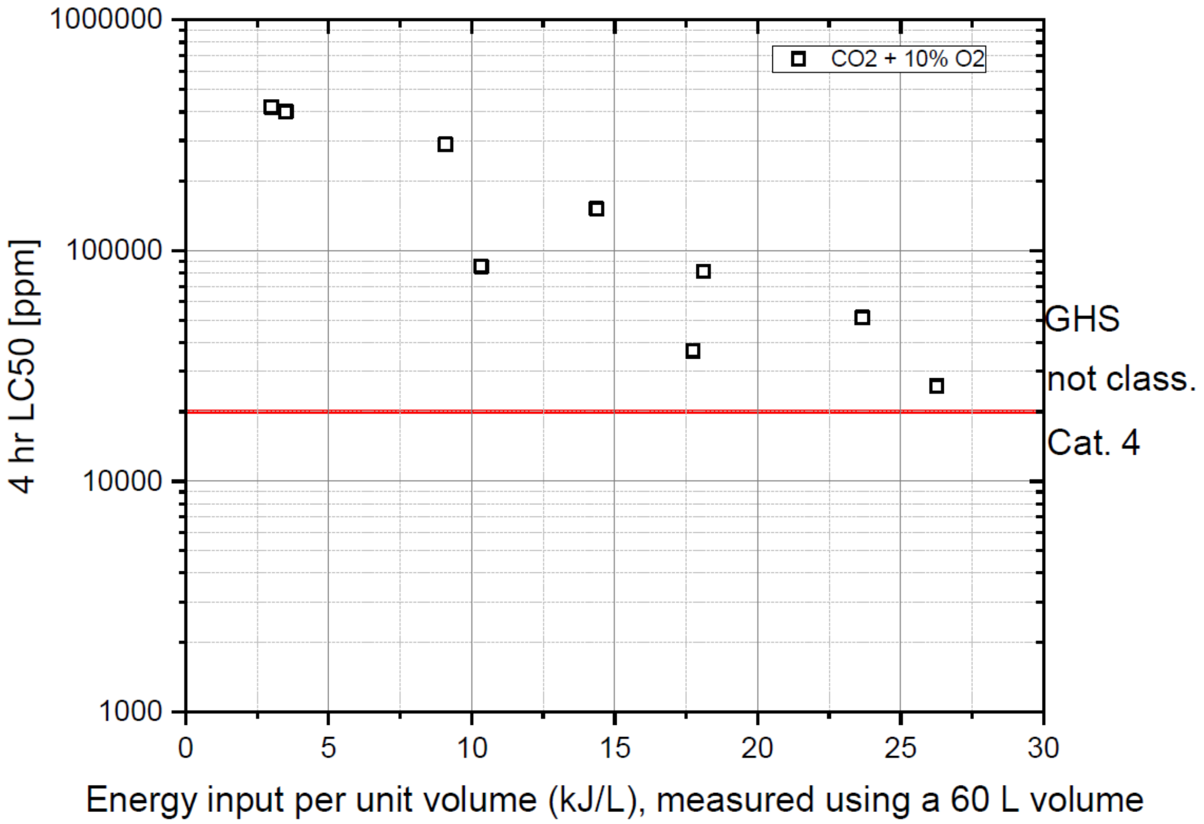

Figure 7. Acute toxicity of the gas mixture in a live-tank circuit breaker-based test device, plotted as a function of the arc energy input (normalized to the 60 L volume of the test device).

Based on the gas analyses mentioned above, it was concluded that the gas mixture in the CO_2 and O_2 circuit breaker even after a large number of short-circuit current interruptions is not classified as toxic according to GHS.

CONCLUSION

A 145 kV CO_2 / O_2 live-tank circuit breaker with a short-circuit current rating of 40 kA and a nominal current rating of 3150 A has been developed for 50 Hz networks. With the help of finite element method simulations, design changes were made to address the lower dielectric breakdown strength of CO_2 compared to SF_6, and the same margin with respect to dielectric capability was achieved for the CO_2 circuit breaker as for SF_6 circuit breakers. A key design change was to move both contacts. The higher speed of sound and higher adiabatic coefficient of CO_2 were also taken into account in the design—the compression volume was increased in size and minor modifications were made to improve the robustness of the design. As a result, the circuit breaker passed all the type tests required by the IEC 62271-100 standard and exhibited very good performance in the T100a test by performing a large number of additional operations and exceeding the requirements of the standard. Finally, the gas mixture was analyzed after exposure to a high arc energy input and found to be not classified as toxic according to GHS. Thus, the extensive experience, knowledge, and numerical simulation capabilities that have resulted from investment in SF_6 technology could now successfully be targeted to rapid development of high-performance CO_2 / O_2 live-tank circuit breakers that maintain and build upon the reliability of this foundation.

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