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Voltage-Current Characteristic of Free Burning Arcs in SF_6 Alternative Gas Mixtures

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***Abstract*—Voltage-current characteristics of free burning arcs in SF_6 and air have been known for decades. As the demand for an SF_6-free solution is increasing, there is an accompanying need to determine arc parameters in the alternative gases. An unblown arc experiment has been established to determine the voltage-current characteristics of SF_6 alternative gases, which have not yet been thoroughly studied. In this experiment free burning arc measurements were performed in a number of gases under consideration of SF_6 alternatives, including CO_2 and mixtures of CO_2 / O_2 with and without C_4F_7N or $C_5F_{10}O$ additives at concentrations of up to 10 %. Measurements were also performed in air and SF_6 for comparison. Arc voltage was measured in each gas at pressures ranging from 1 bar to 5 bar absolute, and electrode separations ranging from 20 mm to 95 mm. Voltage-current characteristic measurements for air and SF_6 show good agreement with previously published results. A linear relationship of the arc voltage to the arc length is shown, as well as fourth root dependence of the arc voltage on the gas pressure. It was shown that neither the O_2 nor the fluorinated additives to CO_2 have any significant influence on the voltage-current characteristic. The minimum arc voltage in all measured gases was slightly higher than in SF_6, but the arc in SF_6 was the least stable and had the highest elongations resulting in high voltage peaks. The arc voltage in air had a similar minimum value to the CO_2 based gases, but the arc was much more stable, resulting in lower effective voltage, especially at low currents.**

***Index Terms*—Article submission, IEEE, IEEEtran, journal, LaTeX, paper, template, typesetting.**

I. Introduction

EXPANSION of gas insulated substations (GIS) with SF_6-free solutions in the medium and high voltage electric energy distribution market has been accelerating in recent years. With the increasing demand for the new SF_6-free gas-insulated switching devices, there is also a need for research investigating arcs switching in alternative gases. Hence, the High-Voltage Laboratory of the Swiss Federal Institute of Technology Zurich (ETHZ) has started a comparative test program for non-SF_6 gases [1].

The research was started with an investigation of the free burning arc and its voltage. It was shown that for bus-transfer switching in disconnectors, successful arc extinction occurs when the arc voltage is higher than the instantaneous recovery voltage [2]. This extinction criterion requires knowing the arc voltage for a given used gas type, gas pressure and electrode separation. The voltage-current characteristics of free burning arcs in SF_6 and air have been known for decades [3] [4]. There has been no published extensive investigation of the voltage-current characteristic of CO_2-based gas mixtures containing C_4F_7N and $C_5F_{10}O$. Available research of CO_2 / C_4F_7N mixtures address only high concentration of C_4F_7N [5].

To go beyond the state-of-the-art, the free burning arc voltage-current characteristic has been measured for the gases containing C_4F_7N and $C_5F_{10}O$ at 5 % and 10 % concentration in a base gas of CO_2 / O_2 in which O_2 always has 10 % concentration and the concentration of CO_2 is adjusted accordingly. It was reported that increasing the O_2 content in CO_2 / O_2 gas mixtures improves the arc switching performance in gas insulated high voltage circuit breakers [6]. Hence the influence of the O_2 concentration in CO_2 / O_2 mixtures was measured for mixtures with O_2 content varying from 0 % to 30 %, to observe if the O_2 will also change the behavior of the arc in free burning condition. As a reference, the arc characteristic in SF_6 and air was also measured.

In addition, for each gas the characteristic was measured for a pressure range from 1 bar to 5 bar and electrode separation range from 20 mm to 95 mm, to investigate influence of these parameters, as well as to study if all gases follow the same trends. All pressures in this publication are given as absolute values.

II. Methods

A. Unblown Arc Experiment

The unblown arc experiment setup, used to research free burning arcs, was built using a vessel from standard GIS. The volume is approximately 353.5 l. A horizontal arc is ignited by the separation of two movable arcing contacts actuated by pneumatic drives. In Fig. 1, photos of unblown arc experiment with the description of the parts are presented. For the arcing contacts, a pin-to-pin configuration was chosen. Pin tips were made of Cu/W (20/80 wt%) with a diameter of 8.4 mm and length of 14.4 mm. A prototype of a so-called *Flexible Pulsed Current Source* (FPCS) developed at the High Voltage Laboratory (HVL) of ETHZ supplied the current for the experiment. This power-electronic based source can provide current waveforms with arbitrary shapes of up to 3 kA, with a supply voltage of up to 5 kV. More information about similar predecessors to this current source with lower ratings can be found in articles from Ritter *et al.* [7] and Walter *et al.* [8].

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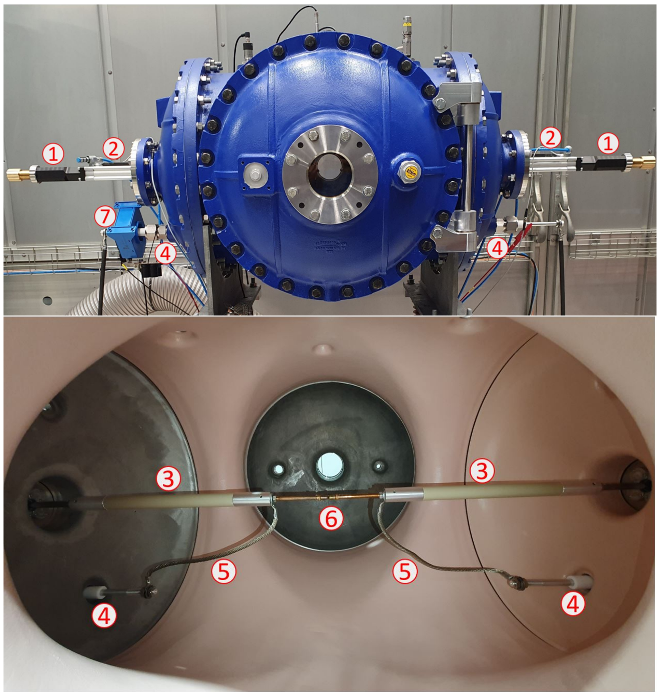

Fig. 1. Outside (top) and inside (bottom) of the unblown arc experiment test device. 1: stroke regulation, 2: drive, 3: insulating rod, 4: current feedthrough, 5: flexible current connection, 6: pin contacts, 7: current transducer

The diagnostics used to perform the experimental measurements include:

- Current-transducers: LEM LT 4000-S (system accuracy $\pm 0.56\,\%$) used for mixtures with C_4F_7N and $C_5F_{10}O$, LT 2005-S (system accuracy $\pm 0.39\,\%$) with all other gases
- Differential voltage probe: Cal Test Electronics CT4079-NA (accuracy $\pm 2\,\%$)
- Contact position - Festo SDAT-MHS (Repeat Accuracy ± 0.1 mm)

The current transducer was changed to a LT 4000-S, as a minor nonlinearity on the decreasing slope was observed while comparing the LT 2005-S measurements with a shunt. The deviation was still within the range of accuracy and had no significant influence on the results, especially considering the fact that the data are binned. It was decided to change the current sensor for measurements with the gases with fluorinated additives to improve the accuracy of energy calculations. All the signals were recorded with a TiePie Handyscope HS6 Diff (14 bit, at sampling frequency 10 MSa/s). In addition, humidity, pressure and temperature were monitored throughout the duration of the measurement series. To ensure a low level of humidity desiccants were used for all gases except in air. The gases used to perform the experimental measurements include:

- Dry air
- SF_6
- CO_2
- CO_2 / O_2 (90 % / 10 %)
- CO_2 / O_2 (70 % / 30 %)
- CO_2 / O_2 / C_4F_7N (85 % / 10 % / 5 %)
- CO_2 / O_2 / C_4F_7N (80 % / 10 % / 10 %)
- CO_2 / O_2 / $C_5F_{10}O$ (85 % / 10 % / 5 %)
- CO_2 / O_2 / $C_5F_{10}O$ (80 % / 10 % / 10 %)

All percentages are given in partial pressure ratio. Dry air has the same composition as ambient air with significantly reduced humidity [9] and will be referred to as air.

The vapor pressure of $C_5F_{10}O$ at 20°C has a value of approximately 0.7 bar [10]. Hence it was decided to use 10 % and 5 % of $C_5F_{10}O$ in the gas mixture which gives partial pressure of 0.5 bar and 0.25 bar respectively. With those two concentrations, the entire application range can be covered. Vapour pressure of C_4F_7N is higher, but it has been decided to use the same concentrations to allow direct comparison.

Gas mixing was done inside the experimental vessel using partial pressure filling and mechanical mixing of the gases with a fan. Typically, the vessel was filled to 5 bar. After finishing the experiments with 5 bar, the pressure was reduced by 1 bar and the experiments were continued in 4 bar. This process was repeated down to 1 bar. For logistical reasons, the measurements with air and SF_6 were performed in the reverse order, with the measurements performed starting from 1 bar, and topping up with fresh gas to 2 bar, repeating up to 5 bar. After the measurements in air, which was the first measured gas, at 3 bar, a galvanic connection of the contacts in the closed position was lost due to greater than anticipated electrode erosion. In consequence, the vessel was evacuated, the overlap of the electrodes was adjusted to reestablish the connection, the vessel was filled with fresh gas to 4 bar, and measurements were continued. After measurements at 5 bar, the pressure was reduced to repeat the measurements at 45 mm for 4 bar and 3 bar. The repeated measurements gave results in the same range as the previous ones. Increased overlap was kept for all following gases.

Separation distances investigated: 20 mm, 45 mm, 70 mm and 95 mm. For air, the separation distance of 70 mm was not measured at 4 bar and 5 bar to minimize contact erosion. Pressure range: 1 bar to 5 bar, with 1 bar intervals.

B. Analysis Routine

For each gas, arc measurements were performed with five pressures and four electrode separation distances. For each set of conditions (gas, pressure, separation) five measurements were done. All experiments used the same nominal current shape, shown in Fig. 2. Before the separation of the arcing contacts, the current was ramped to around 300 A and kept on this “quasi DC” level throughout the contact opening. When the contacts stabilized at their open position (which is shortly after 60ms when the bouncing at the end stop has ceased), the current was ramped to around 3 kA, and then allowed to decay to zero over a time not shorter than 10 ms. The data obtained during the decreasing slope of the current was used for analysis. This current shape was used to minimize contact erosion and gas decomposition during the opening phase. A similar experimental approach was used by Yan *et al.* [11].

The arc time constant is an important property of arcing media, which represents the time required for an arc to stabilize at its characteristic voltage following a change in current [12].

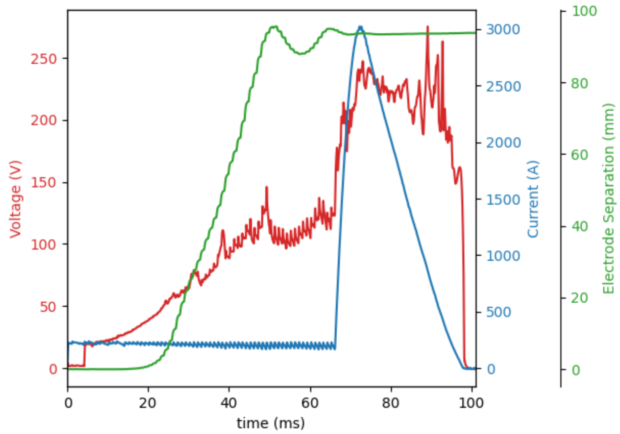

Fig. 2. Sample measurement. Arc voltage (red), current (blue), electrode separation (green)

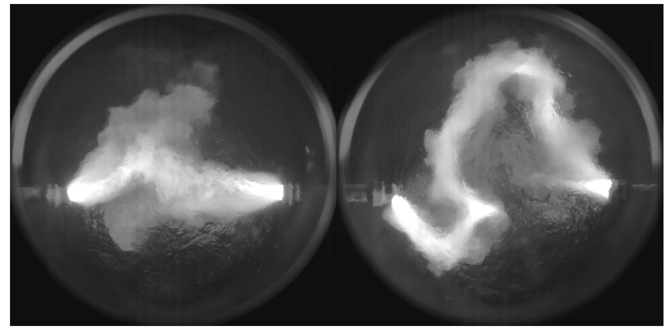

Fig. 3. Two snapshots of arc with high speed camera taken for the arc in SF6 at 5 bar and 95 mm electrode separation.

For vertical free burning arcs in SF_6 in the pressure range from 1 bar to 6 bar, the time constant for 10 mm long arcs was found to be in the range from 10 µs to 15 µs [3]. The same author shows that the time constant for arcs in ambient air in the same configuration at currents higher than 100 A is less than 30 µs. Therefore, the decreasing slope portion of the current pulse has been chosen for analysis, as it has a lower $\frac{di}{dt}$, of not higher than 300 A/ms, which allows for the assumption that the arc is in a stable state (of the voltage in response to the current) during that time. Also, the decreasing slope represents a relevant current condition experienced by disconnectors during switching, approaching current zero from high current.

The voltage probe attachment points were located outside of the experimental vessel, so the stray inductance and resistance of the feedthrough hardware and metallic connection were investigated. Resistance of the internal hardware was measured, and the voltage drop this introduced was subtracted from all results. The inductance was found to be low enough to have a negligible influence on the results in comparison to the voltage measurement accuracy and scatter of the results, hence it was not compensated in the analysis.

Data from five successive arc measurements are combined for the evaluation of the voltage-current characteristic. The data points are binned into segments corresponding to a current range of $\Delta I = 300$ A , e.g. 0 A to 300 A, 300 A to 600 A, etc. Two different types of plots will be presented. The first one shows the minimum measured arc voltage in each current bin (i.e., the minimum arc voltage that corresponds to a current of 0 A to 300 A, 300 A to 600 A, etc.) during the falling slope of the current of all five measurements with identical parameter settings. The second one shows the median arc voltage in each bin for all five measurements, together with the scatter, represented by the 5$^{\text{th}}$ and 95$^{\text{th}}$ percentile of the measured voltage. For all bins a mean value of current is given.

Free burning arcs are known to fluctuate strongly, by elongating and collapsing back to a shorter path, which can be seen on high-speed camera footage obtained during the experiments. Examples of frames taken during measurements with SF_6 are shown in Fig. 3. These fluctuations result in a voltage rise due to the arc elongation. Hence, the plots with the minimum arc voltage vs. current show the arc voltage for the shortest measured arc. This can be an arc along the shortest line between the contacts, although not necessarily. Plots with the median arc voltage and scatter show the trends towards arc fluctuation.

C. Metal vapor influence on arc parameters

The unblown arc experiment was also used to investigate the free burning arc with optical emission spectroscopy [13]. Results of the investigation showed an increase of the arc voltage with the rise of copper vapor content in the arc. For smaller electrode separation distances, the copper vapor pressure is higher, leading to a more significant influence on the arc voltage. Considering those findings, the differences in the arc voltage between measured gasses could be hidden by the copper vapor. This should be the most significant for the small electrode distance, low gas pressure and gases with similar compositions. This would indicate that results should be preferably compared for higher electrode separation distances and higher pressures. Although, for higher electrode separation distances the arc is much less stable, which makes it more difficult to measure the voltage minimum.

In addition, given the fact that the gases were mixed at 5 bar, and then the lower pressure measurements were done in already arced gas, decomposition might significantly lower the content of fluorinated additives at lower pressures. Hence it is expected that the differences between the gases at lower pressures will be much less visible than in higher pressures.

Due to the decomposition of the gas particles, a pressure increase during the course of all experiments for one pressure level was observed. This increase has never been greater than 2 % hence considered insignificant for the results. The pressure increase due to a single experiment was smaller than the pressure sensor measurement uncertainty.

III. Results & Discussion

A. Comparison and Validation of the Results

Free burning arc and its voltage-current characteristic were previously investigated in air [4] and SF_6 [3].

In the publication by Stokes *et al.* [4] voltage-current characteristics of the free burning arc in ambient air are shown

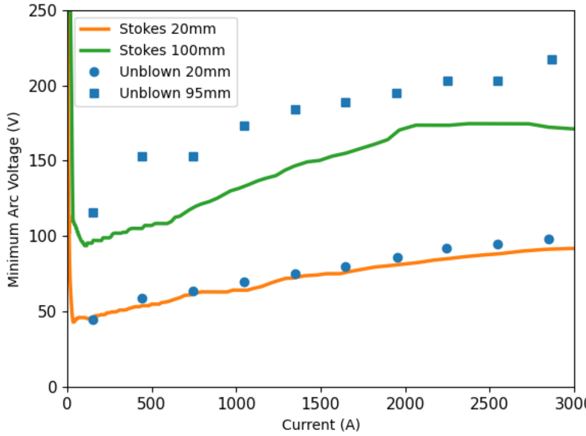

Fig. 4. Minimum arc voltage in air at 1 bar for 20 mm and 95 mm from unblown arc experiment and 20 mm and 100 mm from Stokes *et al.* [4] - acquired with WebPlotDigitizer [14]

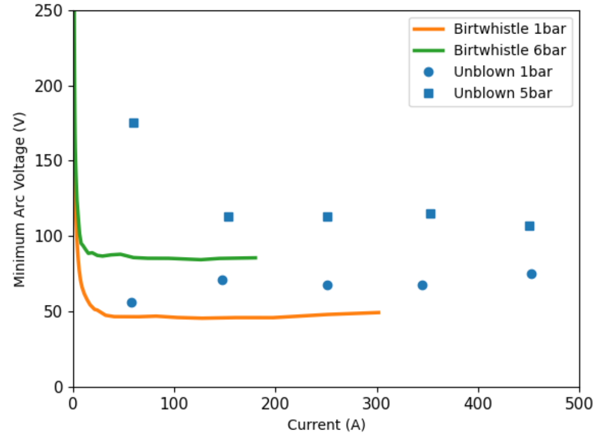

Fig. 5. Minimum arc voltage in SF_6 at 20 mm for 1 bar and 5 bar from unblown arc experiment and 1 bar and 6 bar from Birtwhistle [3] - acquired with WebPlotDigitizer [14]. Bin size changed to $\Delta I = 100$ A to show more data points.

for 5 mm, 20 mm, 100 mm and 500 mm. Investigated arcs were in both horizontal and vertical orientation. Stokes *et al.* results for horizontal arcs with electrode separations of 20 mm and 100 mm were compared with the results from the unblown arc experiment for 1 bar air with 20 mm and 95 mm, Fig. 4. The arc voltage at 20 mm is lower for Stokes by around 10 %. In the comparison of 100 mm and 95 mm, the difference is more significant, especially at lower currents where results from Stokes are lower by up to 30 %, whereas at higher currents the difference is 15 % to 20 %.

Comparison of the voltage-current characteristic in SF_6 at 20 mm from Birtwhistle [3] at 1 bar and 6 bar together with results from the unblown arc experiment for 1 bar and 5 bar are shown on Fig. 5. The minimum arc voltage from the unblown arc experiment is higher for 1 bar by up to 56 %, and for 5 bar higher by almost 100 % for lowest current bin.

Both Stokes *et al.* and Birtwhistle have estimated the voltage minimum along the measured range of currents in order to mitigate the influence of the arc elongation and those estimated values are shown in Fig. 4 and Fig. 5. The results from the unblown arc experiment show the minimum measured values, hence also elongation of the arc influences the results, giving values higher than in the literature, especially in the lower range of currents where the arc is less stable. Considering this and also comparing the raw data shown by both authors which has shown similar scatter, it has been concluded that there is a good agreement between the unblown arc experiment results and results from Stokes *et al.* and Birtwhistle.

B. *Influence of Electrode Separation on Arc Voltage*

The dependence of the minimum arc voltage on the electrode separation distance in CO_2 / O_2 (90 % / 10 %), SF_6 and air in 1 bar and 5 bar is shown in Fig. 6. For each separation distance, only one bin for the current range 2000 A to 2499 A is plotted. This selection was made because the arc in this current range tends to be the most stable.

For each gas, a fit to a linear function was performed. Extrapolation of the linear fit to 0 mm separation distance gives

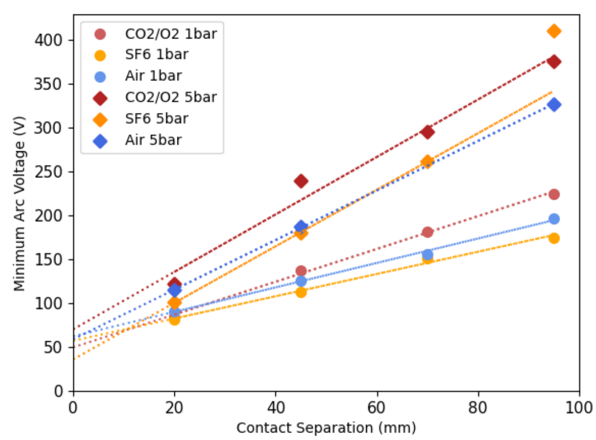

Fig. 6. Minimum arc voltage during current decaying period for bin 2000 A to 2499 A plotted as a function of separation distance for: CO_2 / O_2 (90 % / 10 %), SF_6 and air at 1 bar and 5 bar. Minimum arc voltage measurement for 95 mm contact separation was omitted from the fit for SF_6 at 5 bar

the values from 50 V to 70 V for all shown gases except the SF_6 5 bar which crosses the axis at 36 V.

Arc voltage measured during the opening of the contacts in CO_2 / O_2 (90 % / 10 %) at 3 bar is shown in Fig. 7. As a reference, the minimum arc voltage measured during the decreasing current slope, for the bin 0 A to 500 A for each separation distance are plotted. The dashed red line was fit to the measured voltage between 5 mm to 30 mm. For distances above 60 mm the arc voltage has spikes caused by the arc excursions. After the arc excursion collapses, the voltage drops back to the level around the estimated fit. Measurements of the minimum arc voltage show good agreement with the fit. Minimum arc voltage for 95 mm has values lower than the fit based on one experimental execution. This is expected as with a higher number of experiments the probability of measuring an arc with a length close to the contact separation distance increases. For separation distances lower than 5 mm, the voltage is nonlinear.

A similar linear arc voltage dependence on the electrode

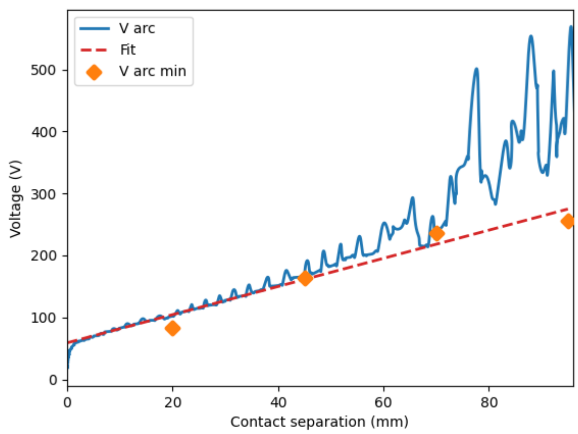

Fig. 7. Arc voltage during the contact separation at steady current of 300 A for one experiment execution in CO_2 / O_2 (90 % / 10 %) mixture at 3 bar final contact separation of 95 mm (blue). The orange diamond symbols indicate the minimum arc voltage for the bin 0 A to 500 A, from all experiments at one separation distance. The red dashed line is a linear fit based on the measured voltage between 5 mm to 30 mm.

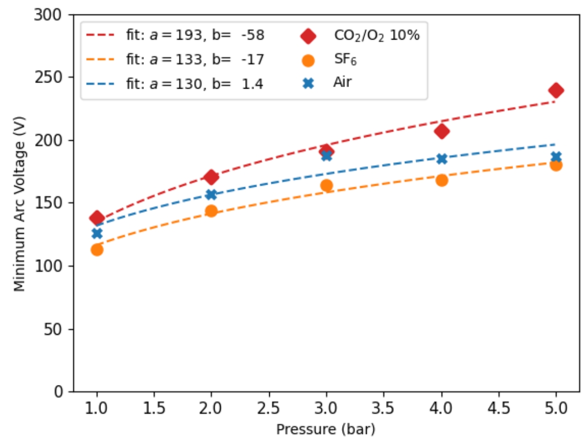

Fig. 8. Minimum arc voltage at 45 mm contact separation, at current bin of range 2000 A to 2499 A for CO_2 / O_2 (90 % / 10 %), SF_6 and air.

separation for separations higher than 5 mm, and nonlinear behavior for shorter electrode separations was shown in literature [15]. The nonlinear increase of voltage is caused by electric field enhancement due to the geometry of the arcing contacts [13] [16]. The electric field uniformity factor for non-arced pins is equal to 0.75 for 1 mm and 0.45 for 5 mm contact separation. Each arc event erodes the surface of the arcing contacts changing its geometry which leads to different field uniformity factor. A more detailed description of this nonlinearity, as well as information about arc temperature and composition affecting the arc voltage, based on the unblown arc experiment measurements, can be found in the article by Engelbrecht *et al.* [13].

It was observed for all investigated gases and almost all pressures that the minimum arc voltage increases linearly with an increase of the arc length. For SF_6 this conclusion can be made only at lower pressures. With the pressure increase, the arc is less stable, especially for higher electrode separation, which means that the measured minimum arc voltage represents an arc path length significantly longer than indicated by the electrode separation. Hence the voltage-separation characteristic cannot be determined, as the arc length is unknown. Therefore the fit for SF_6 5 bar was done without the highest separation as it was visible that the lowest measured arc voltage is much higher than expected. It was also observed that for all gases the length of the arc excursion is increasing with increasing contact separation, which is in agreement with the literature [17].

C. Influence of Gas Pressure on Arc Voltage

To illustrate the gas pressure influence on the arc voltage, bins of range 2000 A to 2499 A for 45 mm separation distance are plotted for CO_2 / O_2 (90 % / 10 %), SF_6 and air in Fig. 8. The 45 mm separation distance between the electrodes was chosen as a compromise between the copper vapor content in the arc and the arc stability. For all presented gases, the arc voltage rises non-linearly with the pressure increase. Only for the air the arc voltage in 3 bar to 5 bar is staying on similar level 188 V, 185 V and 187 V respectively.

In the literature, theoretical calculations were done, as well as experimental measurements in air, showing a fourth root dependence between arc voltage and the gas pressure [18]. A dashed line fit to a fourth root function ($V(p) = a \cdot \sqrt[4]{p} + b$) shows good agreement of this dependency for the gases shown in Fig. 8. A similar dependency was found for all investigated gases at almost all separation distances. The only exception is again for SF_6, where the low arc stability at higher pressures and 95 mm separation distance makes the voltage-pressure dependence in these conditions impossible to determine based on the obtained results.

D. Influence of Oxygen to Arc Voltage in CO_2 and CO_2 / O_2 Mixtures

In Fig. 9, the results of measurements for CO_2 / O_2 mixtures at 95 mm electrode separation at 1 bar and 5 bar pressure are shown. The results are shown for pure CO_2 and two different O_2 concentrations in CO_2 (10 % and 30 %). The top plot shows the measured minimum arc voltage and on the bottom is the median voltage together with the scatter of 5th to 95th percentile. Plots on Figures from 9 to 12 contain the data for multiple gases in order to show the differences in the arc voltage as well as in the tendency of the arc to make an excursion in given gases.

The upper plot of Fig. 9 clearly shows that the minimum arc voltage in all three mixtures is very similar for each given pressure. This is especially true at 1 bar pressure, where the measured minimum arc voltage is around 200 V to 250 V. For 5 bar, the minimum arc voltage is significantly higher, with values between 350 V to 450 V. The minimum arc voltage for 5 bar fluctuates more strongly than for 1 bar, which is a result of the reduced stability of the arc. This trend can also be seen in the lower plot of Fig. 9. Also, the median voltage is higher for 5 bar than for 1 bar, and the differences in the three mixing ratios are small, especially given the amplitude of the scatter bars which indicate the arc voltage fluctuations.

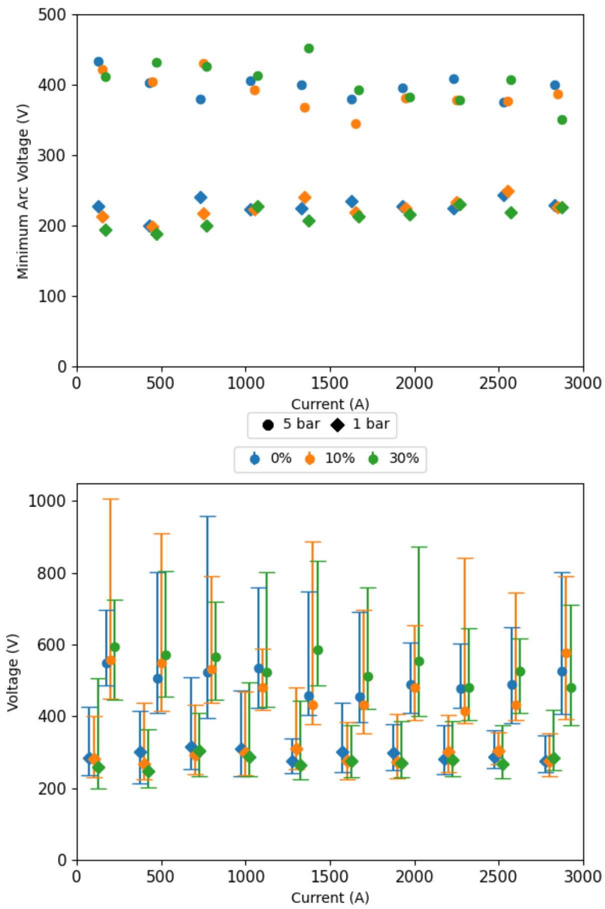

Fig. 9. Minimum arc voltage (top) and median (bottom) vs current for CO_2 / O_2 mixtures with different O_2 content, shown in the legend with %. Pressures are 1 bar and 5 bar shown with diamond symbol and filled circle respectively, contact separation of 95 mm. To improve readability, plotted current values are artificially distributed around the mean of the current bin in both plots, in addition in the bottom plot data points are moved by +50 A at 5 bar and -50 A at 1 bar.

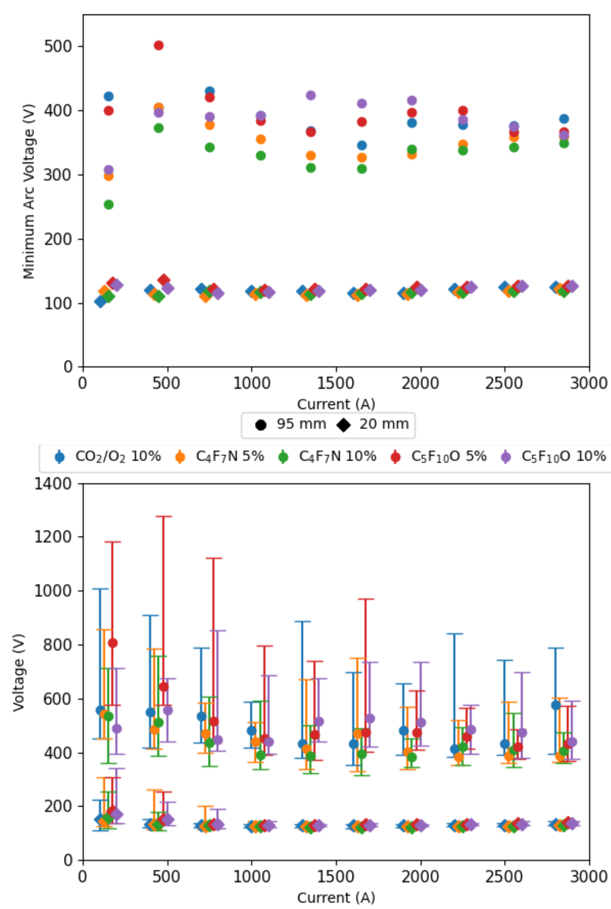

Fig. 10. Minimum arc voltage (top) and median (bottom) vs current for CO_2 / O_2 (90 % / 10 %) and CO_2 / O_2 mixtures with fluorinated gas additive. Pressure 5 bar, Contact separation 20 mm and 95 mm. To improve readability, plotted current values are artificially distributed around the mean of the current bin in both plots, except 95 mm in the top plot.

Over the full range of pressures and separation distances analyzed, no significant influence of the oxygen concentration on the arc voltage was observed in free burning arcs.

E. Comparison of C_4F_7N and $C_5F_{10}O$ Gas Mixtures

Fig. 10 shows results of the measurements at 5 bar with 20 mm and 95 mm electrode separations for the mixtures with C_4F_7N and $C_5F_{10}O$ each at 5 % and 10 % concentrations. In addition, the results for CO_2 / O_2 (90 % / 10 %) are given, as this was the carrier gas for all mixtures with fluorinated compounds.

The minimum arc voltage for 20 mm electrode separation for all gases is typically between 110 V to 125 V. The voltage median for this case shows a similar tendency. All gases have a similar voltage median and scatter, in the range from 110 V to 150 V, for currents above 1 kA. Below this current, the scatter rises significantly for all gases. Plots with the 95 mm electrode separation show much more fluctuation in the minimum arc voltage, from 250 V to 450 V, and higher scatter over the full current range. This shows much higher arc elongation for the larger separation distances, which is visible over the full range of pressures. Increasing the contact separation distance increases both the minimum and median arc voltage, in addition to increasing the scatter caused by arc elongation.

Voltage-current characteristics at 5 bar show that the minimum arc voltage measured in mixtures with C_4F_7N is always lower than that of the base gas, which is consistent with the results in the literature [5], however at lower pressures this is not always the case. This is to be expected considering the gas decomposition leading to a lower fluorinated additive level and assuming a higher fractional metal vapor content of the arc at lower pressures [13]. Characteristics for $C_5F_{10}O$ mixtures show results of both higher and lower minimum arc voltage across all varied parameters. Considering the high arc fluctuation and number of measurements, all observed differences between the CO_2 /O_2 and its mixtures with C_4F_7N or $C_5F_{10}O$ are in the range of the scatter, and therefore are considered to be insignificant.

F. Comparison of SF_6, Air and Alternatives

The comparison between SF_6, air and novel alternatives, is shown in Fig. 11. As it was shown in the previous subchapter

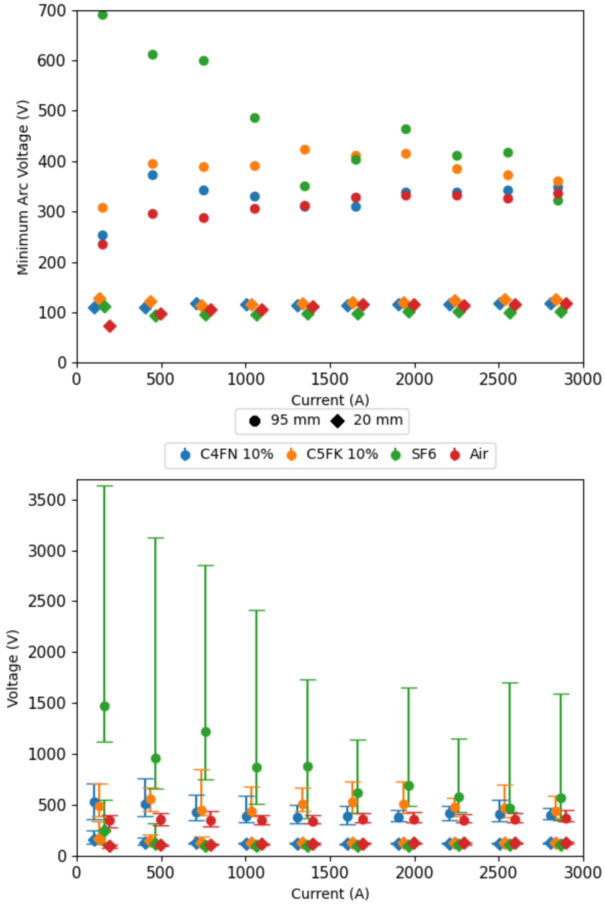

Fig. 11. Minimum arc voltage (top) and median arc voltage (bottom) vs current for SF_6 and alternatives in 5 bar, 20 mm and 95 mm. To improve readability, plotted current values are artificially distributed around the mean of the current bin in both plots, except 95 mm in the top plot.

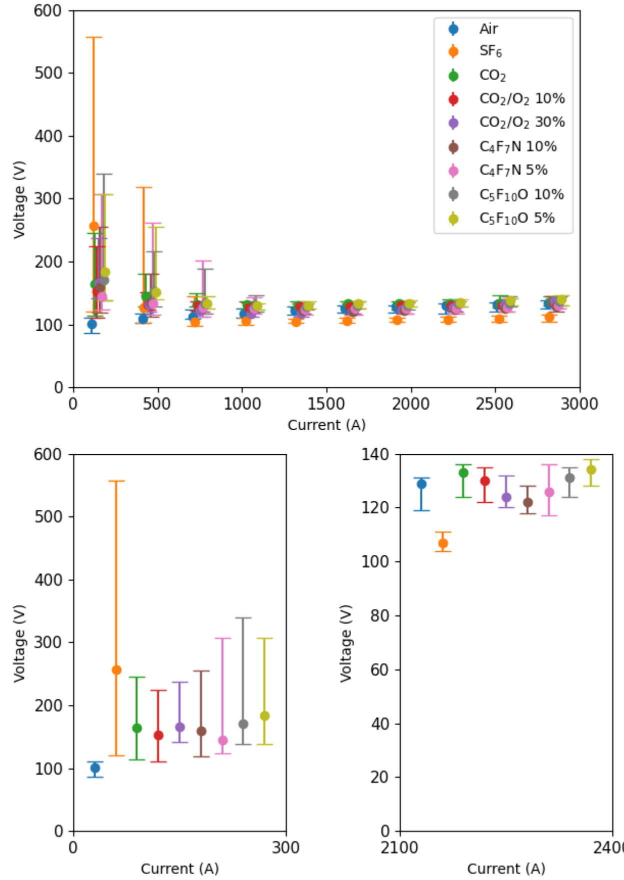

Fig. 12. Median arc voltage with scatter vs current for all measured gasses at 20 mm (top), zoom to bin with current range from 0 A to 300 A (bottom left) and to bin 2100 A to 2400 A (bottom right). To improve readability, plotted current values are artificially distributed around the mean of the current bin in top plot, and in the bottom plots, bins were equally distributed over the x-axis.

that all CO_2 / O_2 mixtures with and without fluorinated additives have similar arc voltage, only mixtures with 10 % of C_4F_7N and $C_5F_{10}O$ are shown in these plots.

In the case of 95 mm electrode separation, the fluctuation of the arc minimum is higher, especially for SF_6, which ranges from 330 V to 650 V. The voltage minimums for the fluorinated mixtures are in the range of 230 V to 430 V. The least fluctuation is evident in the results for air, in which the minimum and median arc voltage are around 300 V for almost the full current range. The voltage median and scatter plot show extremely high scatter for SF_6, much higher than for all the other gases.

The clear difference between the arc voltage in SF_6 and other gases for 20 mm shown in Fig. 12 is even more significant considering that for this condition the arc voltage is most likely highly influenced by the copper vapor [13].

The arc voltage of SF_6, whenever the arc is stable, is lower than that of the other measured gases, which is also visible in Fig. 6 and Fig. 8. However, the arcs in SF_6 are generally much less stable than in the other presented gases. As a result, measuring the true minimum arc voltage for higher separation distances would require a much higher number of experiments. The arc voltage in SF_6 will be lower than in all other measured gases whenever the current is high enough to keep it stable. However, when the current drops below this level (e.g. approaching current zero) the arc becomes less stable, resulting in high elongation, increasing the effective arc voltage. Approaching current zero, arcs in SF_6 alternatives will show less elongation, resulting in lower effective arc voltage. In the air, the voltage minimum is in the same range as for all CO_2 based mixtures, but the arc is significantly more stable across the full range of currents, pressures and separation distances.

IV. Conclusions and Relevance for Switching Devices

The unblown arc experiment has a geometry which is independent from any type of switching device. Therefore results obtained during the experiment cannot be a direct measure for the performance of the gas in a real switching device, but can be treated as an indication of the possible arc extinguishing capabilities of the gases. The switching duty which is the closest related to the experimental setup is bus-transfer switching, described in IEC 62271-102 and realized by a disconnector. The arc extinction in bus-transfer switching takes place with short contact separations and at high pressures [19] hence results for 20 mm and 5 bar are the closest related to this switching duty. Fig. 12, shows the median and a scatter of arc voltage for all measured gases at 20 mm and 5 bar. Within the current bin from 0 A to 300 A - which is an indication for the arc voltage approaching current zero, results show the highest median voltage (257 V) as well as 95th percentile (557 V) for the arc in SF_6. For the arcs in all CO_2 based gases, the medians are in the range of 170 V and the scatters range from 111 V to 340 V. The lowest median of 101 V and the smallest scatter ranging from 86 V to 110 V was measured for the arc in air.

As the arc voltage at current zero has to be greater than the instantaneous recovery voltage to extinguish the arc [2], the results indicate that SF_6 would have the highest capability to clear the arc in bus-transfer duty among measured gases. All CO_2 based gases are expected to have similar performance to each other, but lower than SF_6. Air is expected to have the lowest arc clearing capability in bus-transfer switching among the measured gases. In consequence, the arcing contacts would need a larger separation distance at the extinguishing instant for CO_2 based gases than for SF_6 at the same pressure, and an even longer distance would be required for air, resulting in a longer arcing time during contact separation at the same speed.

V. Summary

A free burning arcs in nine different gases, under a number of pressures and electrode distances, have been investigated. The results of the voltage-current characteristics for air and SF_6 showed good agreement with the available literature. A linear dependence of the arc voltage on the arc length was shown, as well as a fourth root dependence of arc voltage on gas pressure. Investigation showed no influence on the arc voltage introduced by adding O_2 into CO_2. Investigation of the gas mixtures containing C_4F_7N and $C_5F_{10}O$ has shown no tendencies indicating a clear influence on the arc voltage introduced by adding those fluorinated gases. All of the SF_6 alternatives have shown to have slightly higher minimum arc voltage than SF_6 at high currents. At low currents, arc instability leads to an increase of the effective arc voltage. The arc stability in all CO_2-based mixtures was significantly higher than in SF_6 and lower than in air.

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