EXPERIMENTAL STUDY ON LEADER CHARACTERISTICS IN ATMOSPHERIC AIR USING A MACH-ZEHNDER INTERFEROMETER

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ABSTRACT

Investigation of long air gap discharges is important to explain insulation problems in UHVDC system. Leader discharge is one of the main phases of long air gap breakdown. In this paper, a long optical path (approximately 4 m) Mach-Zehnder interferometer was set up to determine thermal parameters of leader discharges in atmospheric air quantitatively. The IEC standard positive switching impulse voltage was applied to a 0.93 m p-plane gap. Filamentary column of gas density reduction can be observed in fringe images. The diameter of the column including inner leader channel and outer hot gas is 1.5-3.6 mm with an average expansion velocity of 6.7 m/s and the typical value of average gas temperature is 600-1000 K. The thermal diameter of the leader itself should be less (~1/5-1/3 of the whole column diameter) and the average temperature should be higher.

1. INTRODUCTION

Long air gap discharge is an important and basic subject in the field of high-voltage engineering. UHVDC transmission system up to ±1100 kV has been planned and constructed recently in China to satisfy the energy requirement of large load centres and one of the main problems is to determine the insulation distance. It demonstrates an urgent demand for research on the mechanism and characteristics of long air gap discharges [1]. The Les Renardières Group carried out a series of experiments in 1970s to get a detailed and comprehensive understanding of the fundamental processes of long air gap discharges and the main phases roughly divided to streamer, leader and final jump [2-5]. Streamer discharges are widely studied in variable situations as many types of discharges contain streamer process. However, the formation and evolution of a leader, especially the steamer-leader transition stage, apparently lack enough studies [6].

Leader discharges is characterized by thermal ionization, the existence of which is a symbol to distinguish between streamer and leader. The thermodynamic process plays an important role in the formation and development of leaders [7]. Hence, it is of great value to obtain the thermal parameters of the leader discharges. A significant feature of leader channel is high gas temperature, which results in gas density reduction and changes in refraction index *n*. For detection of these changes, laser interferometry is commonly used for quantitative measurements [8-10], and Schlieren photography and shadowgraphy are usually used for qualitative imaging [4, 11-13].

Interferometry is applied widely to diagnostics of short gap discharges. However, in long air gap discharges, temporal reproducibility is rather poor and the discharge paths vary from shot to shot. The required temporal resolution of measurements is in the order of several microseconds or less and the optical path should be long enough to satisfy the insulation. All these make the application of laser interferometry to long air gap discharges rather difficult [14]. In this paper, thermal characteristics of leader discharges were investigated by means of a long path Mach-Zehnder interferometer. Filamentary columns of lower density corresponding to leader discharges were observed in interference fringe images and the diameter, average expansion velocity and gas temperature of the column were estimated.

2. EXPERIMENTAL SET-UP

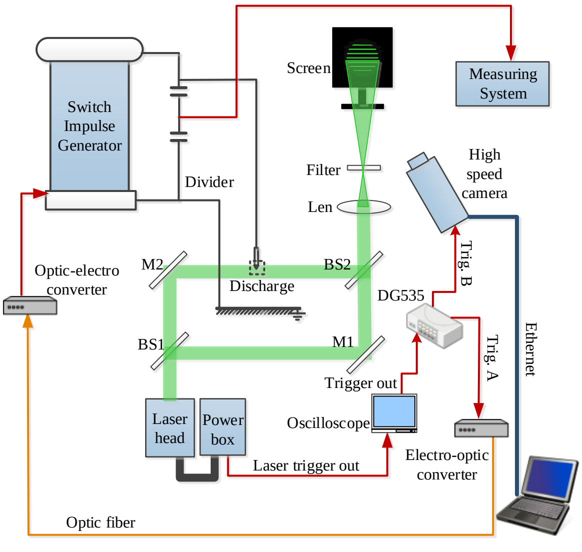


Fig. 1 Schematic diagram of experimental set-up

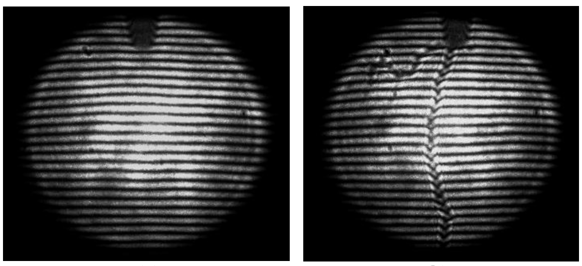
The schematic diagram of experimental set-up is shown in Fig. 1. The measurements were made for a 0.93 m point-plane air gap at atmosphere pressure and the IEC standard positive switching impulse voltage was applied to the gap. The rise and half-wave time of the waveform are 250 μs and 2500 μs (250/ 2500μs). In the present work, the crest voltage was set to about 350 kV. In this condition leader discharges occurred without air gap breakdown.

The diagnostic method is laser interferometry. A long path Mach-Zehnder (M-Z) interferometer was set up, which was consisted of two beam splitters (BS1 and BS2) and two reflector mirrors (M1 and M2). The light source was a pulsing YAG laser with a xenon lamp as pump light source. The wavelength of the laser is 532 nm and the coherence length is about 2 cm. The laser spot is expanded via a beam-expander to 40 mm of diameter. The pulse width is approximately 10ns, which meet the requirement of temporal resolution and is much shorter than the period of mechanical vibrations. The laser beam was separated into two equal intensity beams via BS1, one passing through the testing region and the other passing through the undisturbed air. The optical path length (the distance between BS1 and BS2) was set to approximately 4 m to reach the requirement of insulation. The changes of refraction index n occurring as a result of gas density changes accompanying the leader discharges caused distortion in the interference fringe pattern. The observation region is a circular area near the HV point electrode.

All the instruments were synchronized via an oscilloscope and a digital Delay/Pulse Generator DG535. When the xenon lamp of the laser begins pumping, the oscilloscope is trigged by the laser trigger-out signal (~15 V pulse) and outputs a TTL trigger-out signal to the digital Delay/Pulse Generator DG535 after ~30 ns which can be neglected as the duration of discharges is in order of tens to hundreds of microseconds in the present work. Then, one output channel of the DG535 triggers the switching impulse generator after an adjustable time delay T_A. The time delay between the signal and the impulse voltage inception is less than 2 μs. Another trigger signal of the DG535 is transmitted to the high speed CMOS camera to capture the laser pulse as the pulse width is 10 ns. The exposure time was set to 1 ms. The laser head outputs the pulsed laser beam ~332 μs the xenon lamp pumping. Thus, the fringe images at different times T ($T \approx 330$ μs-T_A) after the impulse inception can be obtained via setting different time delay T_A. Only one image can be obtained in each discharge process since the maximum frequency of the laser is 10 Hz and the duration of discharge is several hundreds of microseconds. In this work, the range of T is from 60 μs to 260 μs at intervals of 20 μs.

3. EXPERIMENTAL RESULTS

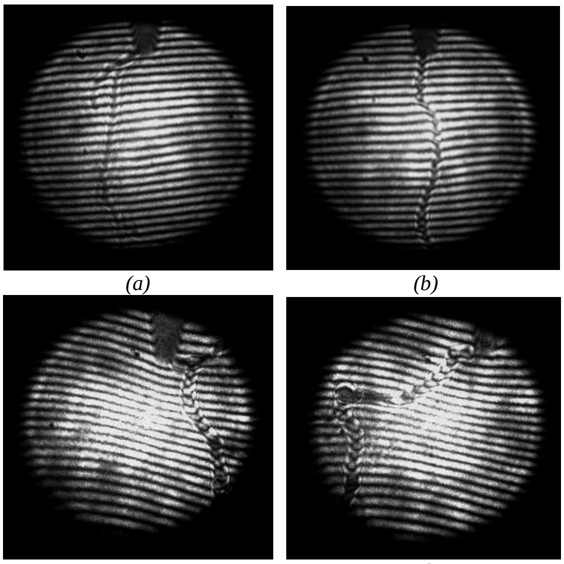
The typical fringe images are shown in Fig. 2. In the fringe images the contour of point electrode can be recognized. The path of leader channels can be observed clearly in Fig. 2(b) as the distortion in fringe pattern indicating the changes in gas density caused by leader discharges is significant compared with the paralleled fringe pattern in Fig. 1(a).



(a) *(b)*

Fig. 2 Typical laser interference fringe images
(a) without discharge; (b)with positive leader discharge.

The diameter of the filamentary column of gas reduction corresponding to leader discharges can be measured from the fringe images via a graph digitiser, regarding where the distortion begins as the boundary. This boundary represents the place where the gas temperature descends to the room temperature and the gas density is closed to the ambient air. The diameter of the column almost retains constant along its length in most fringe images. Fig. 3 shows four typical fringe images obtained at different times and gives the value of the column diameter.



(a) (b) (c) (d)

Fig. 3 Typical fringe images obtained at different times T after impulse voltage inception
(a) T=60μs, D=1.942mm; (b) T=120μs, D=2.343mm;
(a) T=200μs, D=2.647mm; (b) T=260μs, D=2.921mm.

Fig. 4 summarizes the column diameter as a function of time after impulse voltage inception. Experimental results show that the typical value of column diameter is 1.5-3.6 mm. The diameter of the lower density column increases with time as discharge development and the statistical average expansion velocity is about 6.7 m/s.

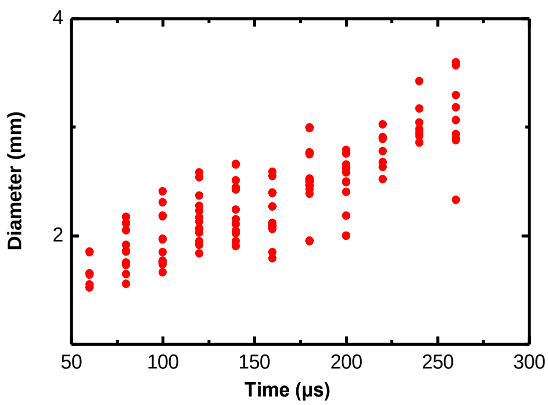


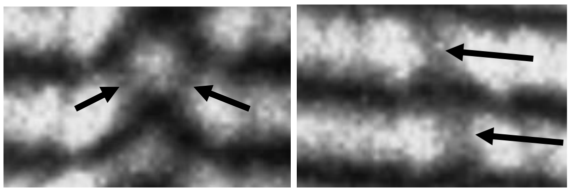
Fig. 4 Filamentary column diameter as a function of time after impulse voltage inception

4. DISCUSSION

The typical value of 'thermal diameter' of leader channel given by J.N. Ross using time-resolved Schlieren photography is 0.3-1.2 mm in similar conditions [4]. The results given above are several times larger than this value because of the different criterion used to determine the boundary. Schlieren photograph indicates the change in gradient of refraction index and the boundary of leader channel was assumed to where the rate of change of density is greatest. The lower density column observed in interference fringe image consists of two parts, the inner leader channel and the hot gas outside. The method mentioned above gives the diameter of the both parts. Thus, the diameter of the main leader channel should be less than the value shown in Fig. 4.

In part of fringe images, we can observe two bands or single band with significant reduction in optical intensity inside the distortion region along bright fringes as Fig. 5 shows (pointed by arrows), which is caused by the sharp gas density reduction. The width of the region between the two bands or of the single band is about 1/5-1/3 of the diameter obtained using the method in section 3. The width of this region has a good agreement with the value given by Schlieren technique. A. Kurimoto et al. used Schlieren technique and interferometry to determine the parameters of negative DC corona, and the width of the region of sharp reduction in density evaluated from interferometry corresponds to the diameter of filamentary column obtained from the Schlieren records [8].

The 'luminous diameter' of leader obtained by still camera photograph is 1-8 mm for air gaps in order of meter [4]. The 'thermal diameter' of leader channel is generally less than the 'luminous diameter'. Since leader discharges mainly depend on thermal ionization, the value of 'thermal diameter' should be used in modelling instead of that of 'luminous diameter'.



(a) (b)

Fig. 5 The region of sharp reduction of gas density
(a) two dark bands; (b) single dark band

A significant advantage of interferometry over Schlieren technique and shadowgraphy is that the gas density reduction or gas temperature can be derived quantitatively from the fringe pattern distortion. The average refraction index of the whole column including leader channel and hot gas was calculated from the diameter and fringe displacement. The average gas temperature was calculated using the Gladstone-Dale formula with the assumption that the pressure in the column is 1 atm. The typical average temperature is 600-1000 K and the average temperature of the leader channel should be higher.

5. CONCLUSION

A long path (approximately 4 m) Mach-Zehnder interferometer was applied to the study on thermal parameters of long air gap discharges. The IEC standard positive switching impulse voltage was applied to a 0.93 m point-plane atmospheric air gap and interference fringe images at different times were recorded.

Filamentary column of gas density reduction caused by leader discharge can be recognised since the significant distortion of fringe pattern. The column consists of the inner leader channel and the hot gas outside. The diameter of the whole channel is 1.5-3.6 mm and the average expansion velocity is about 6.7 m/s. The width of the region of sharp density reduction is about 1/5-1/3 of the whole column diameter and it has a good agreement with the 'thermal diameter' of leader obtained by Schlieren technique. The typical average temperature of the whole column is 600-1000 K and the average temperature of the inner leader channel should be higher.

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