DC Arc Fault: Characteristic Study and Fault Recognition

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***Abstract*- DC arc fault introudces major safety concerns in a wide variety of power electronic applications. However, the randomness and instability of dc arc makes it difficult to be detected. In this paper, an experimental system to study the characteristics of series dc arc is designed and different tests were conducted in order to determine the influence of different factors to the arc such as gap length, current, etc. During the experiments, the load current was varied from 6 A to 30 A and dc source voltage was changed from 75 V to 300 V. Also, dc arc fixed power supply voltage and load current but changing gap length were conducted to examine the influence of arc length. Based on the experimental results, a primary V-I characteristics study was carried out. Current variation analysis was performed to investigate the pulse patterns of the arc current for detection purposes. The results of this paper provide insights of the dc arc characteristics as well as methods for dc arc fault detection.**

I. INTRODUCTION

DC arc faults could occur in the electrical systems of electric vehicles, ships, aircrafts, photovoltaic plants, variable speed drives, utility energy storage units, and any other applications that involve high voltage dc buses [1-3]. If not detected and extinguished on time, the arc faults could spread to adjacent circuits and endanger the power sources, control systems, or even cause explosions in a confined space due to the growing arc pressure.

The characteristics of DC arc have been studied in both frequency and time domain. In the frequency domain, DC arc detection methods have been presented in [3-4]. In [3], back propagation neural network analysis is used along with a Fast Fourier Transform (FFT) method in order to detect dc arc in spacecraft systems. In [4], with wavelet packet based analysis, dc arc energy in different sub-bands is quantified into one variable by using the reconstruction coefficients in each band. These methods give insight into the frequency characteristics of a dc arc and also present the challenges in arc detection, such as noise recognition, calculation time reduction, differentiation from load changes, etc.

Besides frequency domain based detection methods, in [5] and [6], resonant circuits are used to detect dc arc by identifying high frequency oscillations produced by it. In [7], statistical methods are adopted to identify arc by studying the variance of arc (voltage or current) signal. Lastly, in [8], for automotive applications, voltage and current sensors at two different locations in the electrical circuit are utilized to detect anomalies caused by dc arcs. Although many methods for dc arc detection have been studied, a simple, accurate, reliable and cost effective solution is still needed. To assist dc arc related standard development, more experimental supported theoretical studies of the characteristics of dc arc are needed.

Based on the location with respect to the load, the arc faults can be classified into two types: series and parallel. Between these two types of faults, the series arc faults are more common, which is often caused by loose connectors, terminals and so on [9]. Thus, it will be the focus of this paper.

This paper is distributed as follows; a series dc arc test setup is designed and built to study the dc arc phenomenon, described in Section II. The characteristics of dc arc are studied and presented in Section III. The primary study of the dc arc detection based on the current variation analysis is shown in Section IV. Conclusions based on the study were drawn in Section V.

II. EXPERIMENTAL SETUP AND PROCEDURE

Table I summarizes the experimental conditions for dc arc tests. The copper electrodes used for arc generation are rod-type with a cross section of 0.252 inch in diameter. Before each test, the surface of the electrodes were polished in order to remove the burns from last arcing. A step motor was applied to separate the two electrodes at a constant speed. In this study, the anode rod is held stationary while the cathode rod moves apart. The power supply is composed by a high power variac and a rectifier unit. The load is a variable resistive load bank. Fig. 1 (a) shows the arc generating unit and a free burning arc and Fig. 1 (b) shows the diagram of the entire experimental setup.

TABLE 1. EXPERIMENTAL CONDITIONS

Electrodes material	Copper
Load type	Adjustable resistance
DC source voltage	75 V, 120V, 175V, 240 V, 300 V
Load current	3 A, 6 A, 15 A, 25 A
Gap Length	0.06 in, 0.07 in, 0.08 in, 0.095 in, 0.12 in, 0.14 in

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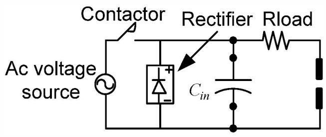
(a) Arc generating unit



(b) Schematic diagram of the experimental system

Fig. 1. Schematic diagram of the experimental system

In order to examine the influence of dc source voltage and load current on dc arc, both changing voltage and current tests were carried out. The experimental procedure is as follows. At first, the dc source voltage is set at 75 V and the load current is controlled to be 3 A, 6 A, 15 A, and 25 A by adjusting the load resistance. Then, the dc source voltage is increased to 120 V and the above 4 load current levels are adjusted again successively. The same procedure is repeated for 175 V, 240 V and 300V dc source voltage.

To investigate the relationship between arc resistance and gap length, dc arc tests with fixed voltage and current but changing gap length were also conducted. During this set of tests, the dc source voltage is maintained at 80 V while the load resistance is maintained at 12 Ohm to achieve the same load current. DC arcs current and voltage were measured under the following 6 different gap lengths: 0.06 in, 0.07 in, 0.08 in, 0.095 in, 0.12 in and 0.14 in.

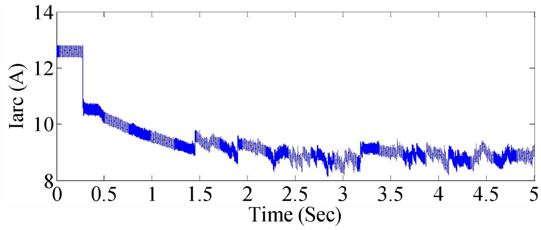
Lastly, in order to study the V-I characteristics of the dc arc, a set of tests were conducted in which the dc voltage was maintained at 80 V. The gap length is 0.08 in while the load resistance was adjusted to achieve different load current levels. The test results were used to analyze the V-I characteristics.

All of the arc signals, including arc current and arc voltage, were recorded using the YOKOGAWA DL850V digital scopecorder. This scopecorder has an analog to digital conversion resolution of 16 bits and the sampling rate used for the tests is 200 kHz. The recording length was 5 seconds although the arc faults lasted longer. Both the arc occurrence and stable arcing were recorded.

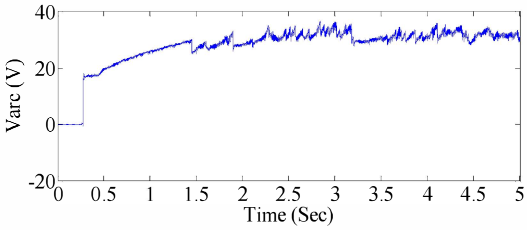
Fig. 2 shows an example of measured arc voltage trace and arc current trace. In this particular example, the dc source voltage is 80 V with a load current of 12.5 A. The rise of the arc voltage and the fall of the load current (arc current) indicate the initiation of the arcing process.

III. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, the experimental results based on the procedures described in Section II are presented. These results show different characteristics of the dc arc in terms of resistance, voltage, current, and variation of these signals for different cases



(a) Arc current trace



(b) Arc voltage trace

Fig. 2. Typical arc current trace and arc voltage trace

A. Arc Resistance

Fig. 3 shows the average arc resistance versus dc source voltage, under different circuit current levels. This figure shows that the dc source voltage has a slight influence to the arc resistance, especially for the arc with lower current levels whereas the circuit current has a more significant influence on the arc resistance. The data point for 75 V dc source voltage and 3 A load current is not included in this figure since the arcing under this condition extinguishes before stopping the electrodes and removing the dc source voltage. The short duration of this arc leads to a smaller average gap length and then influences the arcing parameters. Thus it is not comparable to the other data points which last the whole data recording duration.

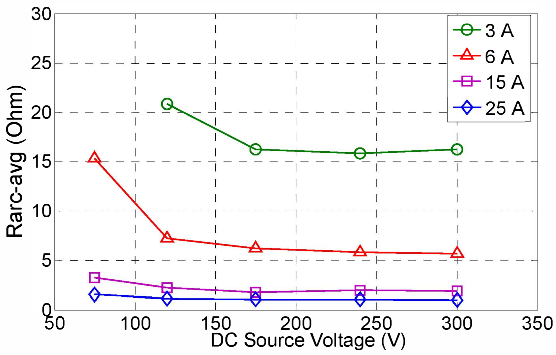


Fig. 3. Average arc resistance

B. Arc Voltage

A plot of the arc voltage versus dc source voltage is given in Fig. 4. In this figure, the arc voltage shows a stable flat trend with the increase of external dc source voltage. However, the load current level has an obvious impact on the arc. It can be seen that the lower load current arcing shows a higher arc voltage level. The data point for 75 V dc source voltage and 3

A load current is not included either for the same reason explained in the previous paragraph.

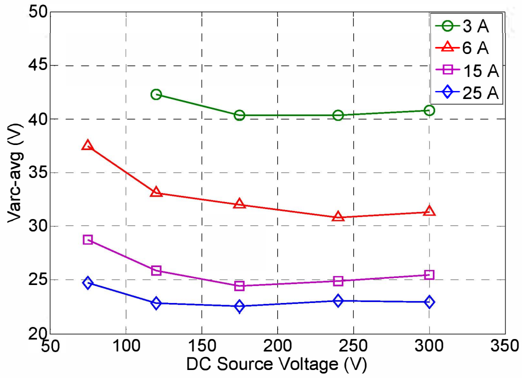


Fig. 4. Average arc voltage

C. Gap Length

The original purpose of this part is to study the influence of arc length; however it is difficult to measure the actual arc length because the arc length keeps changing due to the arcing dynamics. Thus, the gap length between two electrodes is used to approximate the actual arc length. Fig. 5 shows the average arc resistance at different gap lengths. With the increase of gap length, the arc resistance is increased as well which shows a strong correlation between arc length and arc resistance.

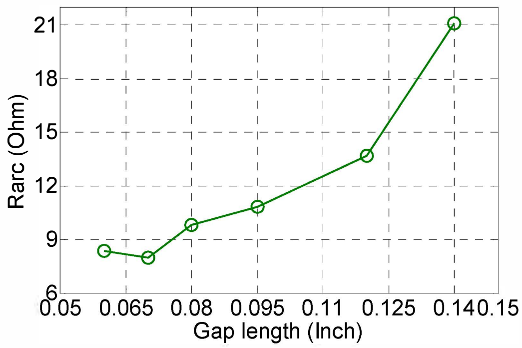


Fig. 5. Average arc resistance versus gap length

D. V-I characteristic

The arc voltage versus arc current is plotted in Fig. 6 with black dots. To achieve a mathematical description of the V-I characteristics of dc arc, the Allometric fitting is applied. The fitting curve is also shown in Fig. 6 by the red line.

The fitting equation describing the V-I characteristics is as follows:

$$V_{arc} = \frac{50.5}{I_{arc}^{0.23822}} \quad (1)$$

This equation provides a primary insight into the electrical behavior of the dc arc. To refine this model, more experimental results considering other parameters are needed. For example, the dependence of arc resistance on the gap length is obvious from Fig. 5 which shows an approximately linear relationship. Thus, the gap length L could also be considered into the V-I characteristics.

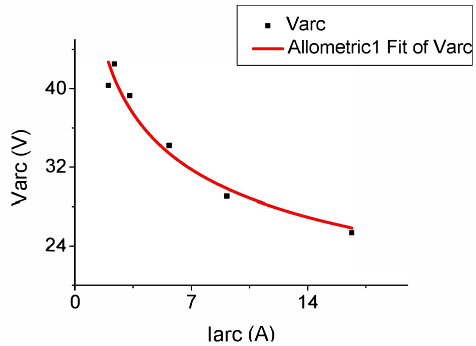


Fig. 6. Average arc voltage

IV. Current Variation Analysis for Fault Detection Purpose

In this section, a primary study of dc arc fault detection is conducted based on the chaotic nature of physical processes of arc. The arc current and arc impedance waveforms are consistently changing, influenced by the evaporation process and combustion of the electrode material, and also influenced by the magnetic field generated by the arc current itself when the arc current is large enough [9]. The chaotic characteristics of the dc arc current are reflected by the pulsed pattern of the current waveform: the current amplitude changes dramatically in a short period. Researchers have been looking into the chaotic characteristics of dc arc [7]. However, these methods involve complex computational procedures.

Thus, in this section, a simple yet effective method, which could be realized with low-cost detectors, is proposed to utilize the chaotic characteristic of dc arc for fault recognition purposes. First, a proper time window T_s is selected, then the maximum and minimum current amplitude I_{max} and I_{min} within each T_s is identified and lastly the difference between I_{max} and I_{min}, I_{dif}, is calculated. The time window should be carefully selected to be long enough to represent current randomness appropriately but it also should not be so long as to reduce the sensitivity. Based on the sampling rate of the oscilloscope and several trial calculations, T_s=10 ms is selected.

Fig. 7 shows the current variation patterns based on the arc traces shown in Fig. 2. The current variation shows three different patterns for different arcing stages. Through the whole arc burning period, an offset of around 0.4 A of I_{dif} is observed. This offset is caused by ripple in the dc voltage generated by the rectifier and is expected to be eliminated if a battery is applied as the dc source instead. When the arc starts, a large I_{dif} is produced by the current drop, which could be a signature of dc arc but would require proper discrimination from the normal current change caused by load change, switching operation [1]. During the arc developing stage, when the electrode was moving, I_{dif} is low and smooth. When the electrodes stopped moving, the current variation pattern shows that the self-sustained arc has high I_{dif} values. The amplitude of the current variation can reach 1 A. A possible explanation of this phenomenon could be the motion of cathode spots [9]. The cathode spots show higher mobility when the arc is continuously burning. These repeating yet unique large I_{dif} pulses could be used to indicate the occurrence of an arc fault. Therefore, I_{dif} could be chosen as one signature of dc arc fault.

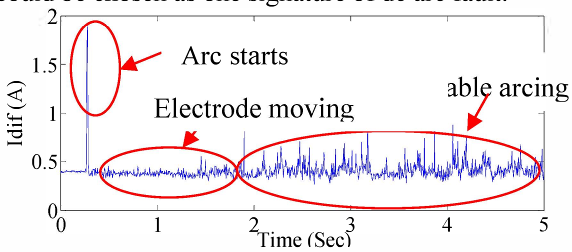


Fig. 7. Current variation at different arcing stage

The average current variation under different dc source voltage and load current level is presented in Fig. 8. In order to eliminate the unwanted low frequency and high frequency noise from measurements, a hardware band pass filter was applied here. The bandwidth of this filter is 1.5 kHz – 45 kHz. The current variation analysis was applied to the filtered arc current signal. Results in Fig. 8 show that both the dc source voltage level and the load current level have influences to the arc current variation. For higher load current level, the current variation is larger. Moreover, the current variation tends to decrease with higher dc source voltage which indicates that although the dc source voltage has little impact on the arc voltage and arc resistance, higher dc source voltage has the ability to stabilize the arc current and make the current variation lower.

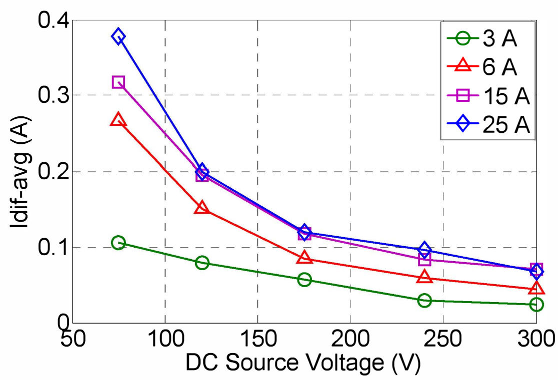


Fig. 8. Average current variation at different dc source voltage and load current level

V. Conclusion

DC arc at different currents, voltages, and gap lengths were measured and analyzed in this paper. The test results show that the arc resistance stays stable with the increase of dc source voltage while it shows a strong dependence to the load current. The arc voltage also shows a loose relation with the dc source voltage especially when the load current is lower. However, through the test results of changing gap length, we can notice that the arc resistance increases with the increase of gap length and it increases faster with larger gap length.

The variation of arc current signals was analyzed as a simple and cost-effective method to indicate the occurrence of dc arc faults. A simple calculation procedure of the arc current variation was carried out to represent the chaotic and dynamic nature of the dc arc physical process. The current variation indicates different stages of the arcing and could be utilized for dc arc fault recognition. The average current variation value for different dc source voltage level and load current level was also analyzed. The results show that the current variation decreases with the increase of dc source voltage especially when the load current is higher. This indicates that although the dc source voltage has little impact on the arc parameters such as arc voltage, arc impedance, higher dc source voltage could suppress the chaotic nature of dc arc in certain degree and make the arcing more stable.

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