Research on AC Arc Fault Characteristics Based on the Difference between Adjacent Current Cycle

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***Abstract*—Arc fault occurs frequently in aircraft system. Once the arc fault occurs, great harm will be caused, so it is necessary to diagnose and eliminate it in time. The physical phenomena of AC(Alternating Current) arc such as light and sound are not obvious when it occurs, because of its zero break characteristic.so it is difficult to detect. Therefore, it is necessary to study AC arc detection. In AC rectifier bridge load circuit, the current waveform under normal condition is similar to the waveform under arc condition, which makes it an aporia to detect AC arc. However, arc characteristics at present such as current change rate, flat shoulder ratio and harmonic component extracted from arc current are not suitable for arc fault diagnosis of rectifier bridge load circuit. Based on the automatic AC arc research platform, the serial and parallel arc faults experiments of the rectifier bridge load circuit are done. The condition of the experiment is 115V/360Hz-800Hz. The randomness of arc is amplified by the difference between adjacent current cycle's. On this basis, the effective value standard deviation of adjacent cycle's difference, the DC(Direct Current) component standard deviation of adjacent cycle's difference and the even harmonic power of adjacent cycle's difference are extracted from time domain and frequency domain respectively as AC arc fault characteristics. By the method of ratio and threshold, this paper verifies that the extracted characteristics are suitable for AC arc fault detection in rectifier bridge load circuits.**

Keywords- rectifier bridge load; AC arc fault; adjacent cycle's difference; time-frequency domain characteristics

I. INTRODUCTION

Arc is a phenomenon that current passing through the insulating medium (such as air). It is caused by the excessive electric field at both ends of the air gap. Vibration, high temperature, water mist, radiation, strong oxidation and other factors in airplane system can easily lead to loosening of wiring, aging of cables, and even insulation damage. Arc faults are easy to occur in loosened wiring or damaged insulation [1]. Once AC arc fault occurs in aircraft system, it is very likely to ignite flammable and explosive materials around the arc, which causes fire and brings a great threat to safety. Therefore, it is necessary to detect and exclude arc fault timely and ensure the safety of the electrical systems.

Arc fault detection methods normally detect arc faults basing on the current, voltage, and the corresponding derivatives of these electrical signatures. Because of the location of arc fault cannot be pre-determined, it usually uses current signal to detect arc fault. According to the signature extracting techniques, arc fault characteristic can be categorized into time domain characteristic and frequency domain characteristic [2]. The main time-domain characteristics are effective value, peak value, average value, changing rate of current, flat shoulder ratio [3]-[7], etc. The time-domain characteristics such as RMS(Root Mean Square), peak value, average value and other characteristics have poor anti-jamming performance. The normal loading and unloading transient process of the system will lead to changes of these characteristics. The changing rate of current increases and the proportion of flat shoulder decreases with the increase of frequency. What's more, the current waveform of rectifier bridge load circuit under normal conditions has flat shoulder section. Therefore, the time domain characteristics extracted at present are either not suitable for the frequency conversion system, or not suitable for the rectifier bridge load and other non-linear load circuit, or poor in anti-interference ability. Frequency domain characteristics mainly include harmonic components, odd harmonic, pink noise characteristics in high frequency [8]-[14], etc. When arc fault occurs, the current waveform is distorted, and the degree of waveform distortion decreases with the increase of frequency. Odd harmonics are suitable for arc detection in linear load system, but not for rectifier bridge load system. Harmonic components within a specific frequency band is extracted for a specific system. Once a harmonic interference within the frequency band occurs in the system, it is easy to cause misjudgment. Therefore, most of the extracted frequency domain characteristics are only applicable to linear loads system, but not to rectifier bridge loads system and other non-linear loads system.

Serial and parallel arc faults of rectifier bridge load circuit are simulated at 115V/360-800Hz condition. The main circuit current signal was collected. Based on the time-domain statistics and spectrum analysis of the adjacent current cycle's difference, the time-domain and frequency-domain characteristic values applicable to 115V/360Hz-800Hz rectifier bridge load system are extracted.

II. EXPERIMENTAL PLATFORM AND DATA ACQUISITION

A. Experimental platform of arc simulation

Fig 1. shows the experimental schematic diagram of AC arc fault, which consists of AC power supply, contactor, resistance

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R, load box, arc generator and sensor. The arc generator is designed according to the standard UL1699, As shown in Fig 2.

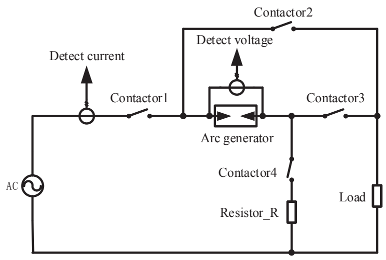


Fig 1. Experimental schematic diagram of AC arc fault

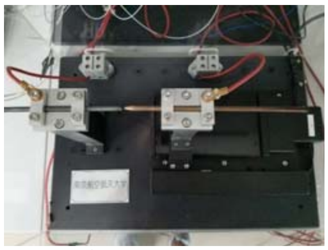


Fig 2. Arc generator

In the arc fault experiment, the arc generator is driven by the stepper motor, and detects the electrode distance by the grating in real time. The arc fault are simulated by controlling the relative position of two electrodes. Meanwhile the resistance (R) is used to limit the output current of AC power in parallel arc fault, preventing shorts circuits. Contactors are used to control the series-parallel connection between arc and loads. Serial arc occurs when contactors 1 and 3 are closed, and parallel arcs occur when contactors 1, 2 and 4 are closed. This paper uses a Hall current sensor to acquire the circuit current.

B. Current waveform

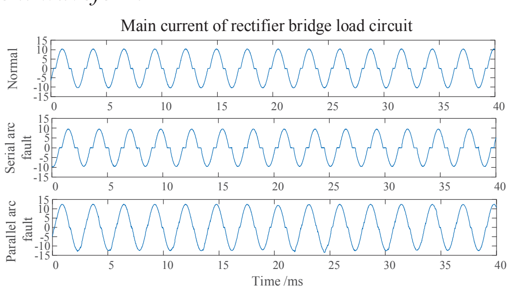


Fig 3. Current of rectifier bridge load circuit

Fig 3. shows the current waveform under normal condition, the current waveform under serial arc fault condition and the current waveform under parallel arc fault condition. It can be seen from Fig.3 that after the occurrence of serial arc, the RMS of current decreases. However, the RMS of current increases after the occurrence of parallel arc. Unlike the sinusoidal current of linear load, the main current of rectifier bridge load circuit has flat shoulder section under normal conditions, which is similar to the waveform characteristics under arc condition. This makes the characteristics of flat shoulder section ratio, current change rate and odd harmonics not suitable for arc detection under rectifier bridge load. It can also be seen that when serial arc occurs, the proportion of flat shoulder section increases, and when parallel arc occurs, the proportion of flat shoulder section decreases. Although the characteristics of flat shoulder section are similar to normal conditions after arc occurs in rectifier bridge load circuit, there are still slight differences between waveforms of different cycles, and there are fluctuations in time domain characteristics.

III. Analysis of AC arc fault characteristics

A. Analysis of time-domain characteristic based on adjacent current cycle's difference

According to the analysis of current waveform in II.B section, there are slight differences in current waveforms of different cycles after arcing, such as the slight difference of current distortion position and current waveform at distortion place. Because of the randomness and instability of arc, the time-domain characteristics of current after the occurrence of arc have a certain fluctuation. This paper distract characteristics based on difference between adjacent current cycles, which is acquired by subtraction between the corresponding sampling point of the current's latter cycle and former cycle. It filters the fundamental component and the inherent harmonic component of the circuit, enlarges the difference of current distortion, and enlarges the fluctuation of time domain characteristics. Taking 115V/400Hz serial arc as an example, the RMS and DC components of each cycle within 100ms are obtained. They are shown in Fig 4. and Fig 5.

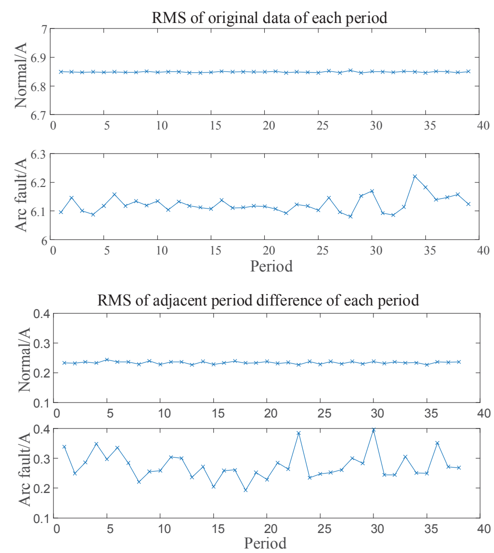
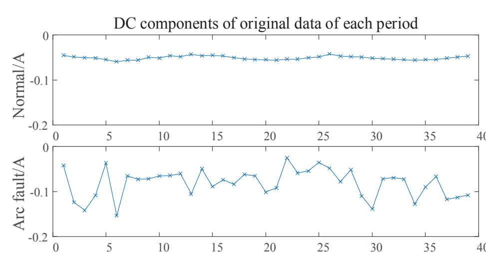


Fig 4. RMS values of each cycle



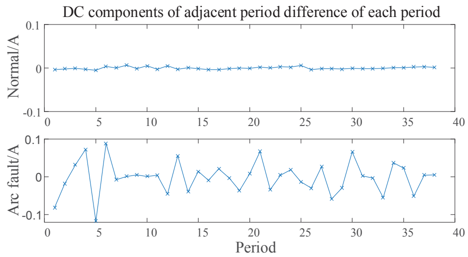


Fig 5. DC component of each cycle

It can be seen from Fig 4. And Fig 5. that the RMS and DC components are almost unchanged under normal conditions, while the RMS and DC components fluctuate obviously under arc conditions. Moreover, the characteristic fluctuations of the RMS and DC components of the adjacent cycle's difference are larger than those of the original data. It is also verified that the adjacent cycle's difference enlarges the arc randomness effectively.

Because of the increasing fluctuation of RMS and DC component under arc fault conditions, the standard deviation in statistics is taken as the object of analysis. The expression of standard deviation of RMS is shown as equation(1), $I_1, I_2, \ldots, I_N$ are separately the RMS of each current cycle within 100ms, N is the number of current cycles in 100ms, STD（Standard Deviation） is the standard deviation, μ is the mean value of $I_1, I_2, \ldots, I_N$, as shown in equation(2).

$$\mathrm{STD} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(I_i-\mu)^2} \tag{1}$$

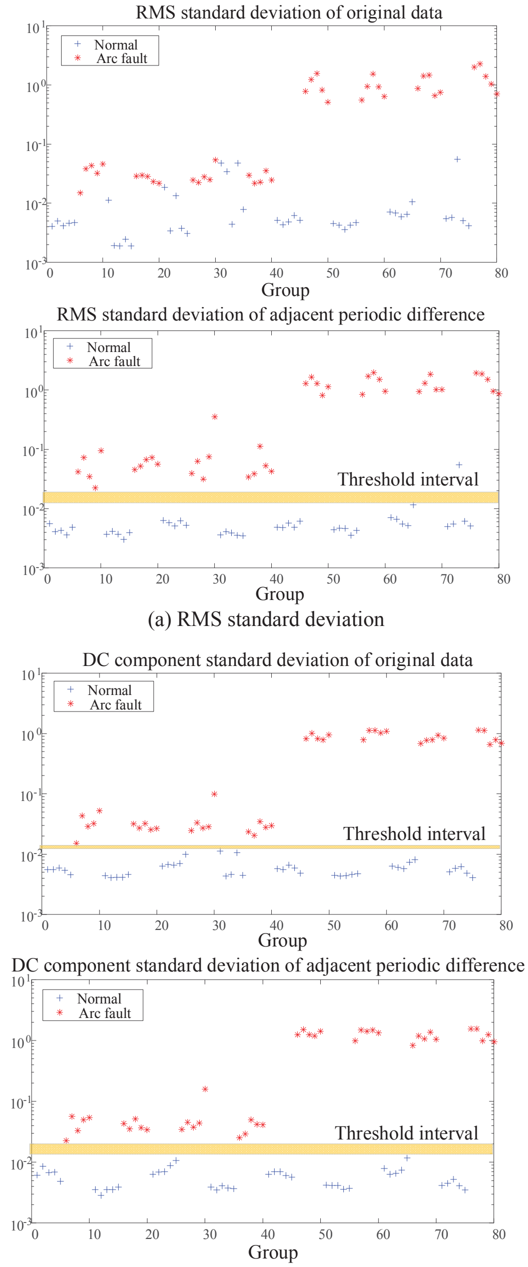
$$\mu = \frac{1}{N}\sum_{i=1}^{N} I_i \tag{2}$$

TABLE I. STANDARD DEVIATION OF RMS OF CURRENT

		Original data			Adjacent cycle's difference		
Type of arc	Frequency	Normal condition (Mean)	Arc fault (Mean)	Arc/Normal	Normal condition (Mean)	Arc fault (Mean)	Arc/Normal
serial	360Hz	0.0045	0.0348	7.73	0.0045	0.0531	11.9
	400Hz	0.0039	0.0263	6.75	0.0037	0.0587	15.8
	600Hz	0.0085	0.0308	3.64	0.0057	0.1121	19.6
	800Hz	0.0284	0.0267	0.94	0.0037	0.0560	15.0
parallel	360Hz	0.0051	0.9832	191	0.0053	1.2342	234
	400Hz	0.0043	0.9213	216	0.0043	1.3975	324
	600Hz	0.0074	1.0340	140	0.0072	1.2228	170
	800Hz	0.0152	1.4834	97.9	0.0153	1.4240	93.3

TABLE II. STANDARD DEVIATION OF DC COMPONENT OF CURRENT

		Original data			Adjacent cycle's difference		
Type of arc	Frequency	Normal condition (Mean)	Arc fault (Mean)	Arc/Normal	Normal condition (Mean)	Arc fault (Mean)	Arc/Normal
serial	360Hz	0.0054	0.0342	6.33	0.0066	0.0430	6.49
	400Hz	0.0043	0.0285	6.68	0.0035	0.0401	11.5
	600Hz	0.0073	0.0424	5.79	0.0079	0.0643	8.12
	800Hz	0.0071	0.0273	3.86	0.0038	0.0373	9.89
parallel	360Hz	0.0057	0.8764	153	0.0064	1.3158	205
	400Hz	0.0045	1.0279	228	0.0040	1.3355	336
	600Hz	0.0067	0.8016	120	0.0080	1.1001	137
	800Hz	0.0052	0.8805	170	0.0043	1.2584	291



(a) RMS standard deviation

（b）DC component standard deviation

Fig 6. Time-domain characteristic values

TABLE I and TABLE II are the RMS standard deviation results and the DC component standard deviation results respectively. It can be concluded from Table 1 that the standard deviation of RMS extracted from the difference of adjacent cycles has been amplified more than 6 times after the occurrence of arc faults. As can be seen from Table 2, the standard deviation of DC component of arc current based on the difference of adjacent cycles is more than 6 times of that of normal conditions. Moreover, the time-domain characteristic extraction based on the difference of adjacent current cycles has a larger discriminant degree than the time-domain characteristic extraction based on the original data. Therefore, the RMS standard deviation and DC component standard deviation of adjacent current cycle's difference can be used as the characteristic to distinguish arc fault from normal condition under rectifier bridge load system.

As can be seen from the statistical charts of time-domain characteristics in Fig 6. , the standard deviation of DC component of original data has a threshold range as well as that of adjacent cycle's difference. However, the threshold range of DC component standard deviation based on adjacent cycle's difference is wider. It is impossible to set a unified threshold to distinguish arc fault condition from normal condition through RMS standard deviation of the original data. When there is a lot of noise under normal conditions, it is easy to cause misjudgment. However, the RMS standard deviation of adjacent cycle's difference has only one normal point extraordinary, and there is a unified threshold interval in other cases.

B. Analysis of frequency-domain characteristic based on adjacent current cycle's difference

From the analysis of II.B section, it can be concluded that after the occurrence of arc, the waveforms of current in each cycle have different distortion positions, and the waveforms of current at zero-crossing are different, especially when parallel arc occurs. This asymmetric distortion will cause even harmonic to change. Therefore, FFT(Fast Fourier Transform) spectrum analysis of current signal is carried out. Taking 115V/400Hz serial arc as an example, the spectrum diagrams of the original data and the adjacent current cycle's difference are drawn, respectively, as shown in Fig 7.

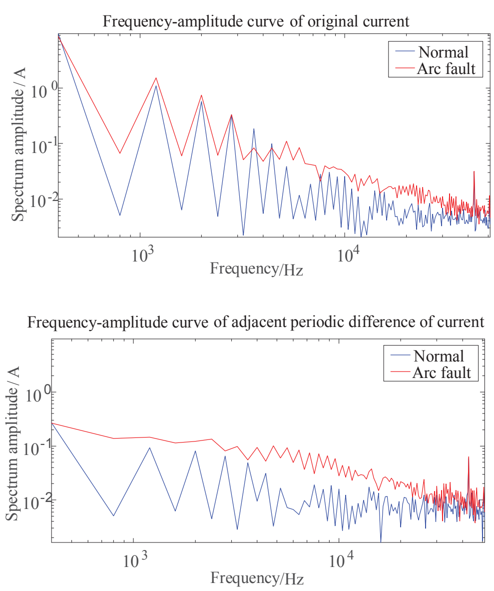


Fig 7. Spectrum

It can be seen from Fig 7. that the odd harmonics of the original data under normal conditions and arc conditions are almost identical, while the odd harmonics of the adjacent current cycle's difference has a certain degree of discrimination, but the discrimination is not very large. In contrast, the even harmonics within 10 kHz under the arc case are much larger than that in the normal case, and the discrimination degree of the even harmonic extracted from adjacent current cycle's difference between the arc and the normal case is greater than that of the original data. It also proves that the randomness of arc can be amplified by the adjacent current cycle's difference. The power sum results of even harmonic within 10KHz are given in TABLE III.

TABLE III. THE POWER SUM OF EVEN HARMONIC POWER WITHIN 10 KHZ

		Original data			Adjacent cycle's difference		
Type of arc	Frequency	Normal condition (Mean)	Arc fault (Mean)	Arc/Normal	Normal condition (Mean)	Arc fault (Mean)	Arc/Normal
serial	360Hz	0.00030	0.0069	23.24	0.00047	0.0117	24.61
	400Hz	0.00022	0.0081	37.55	0.00033	0.0146	44.10
	600Hz	0.00021	0.0183	87.09	0.00026	0.0446	169.1
	800Hz	0.00050	0.0073	14.63	0.00040	0.0118	29.33
parallel	360Hz	0.00016	2.9689	18675	0.00032	4.7128	14887
	400Hz	0.00018	3.6975	21040	0.00040	6.2459	15490
	600Hz	0.00013	2.3647	18625	0.00025	4.1796	16845
	800Hz	0.00022	2.3010	10373	0.00047	3.5836	7624.1

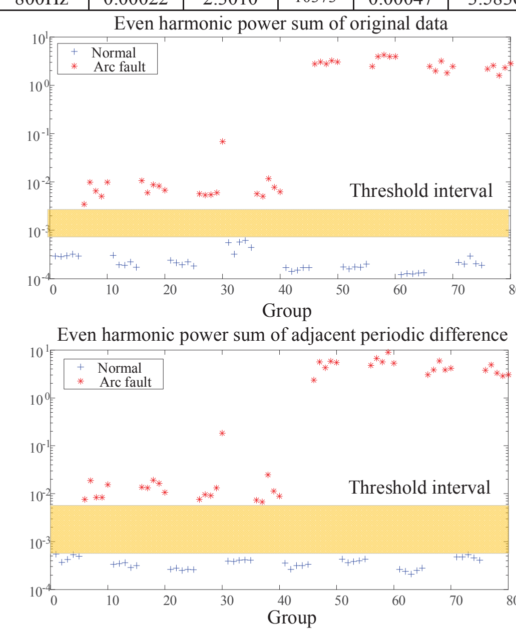


Fig 8. Frequency-domain characteristic values

Table 3 shows that the power sum of even harmonic within 10KHz extracted from original current data are amplified more than 10 times after the occurrence of arc fault. However , the power sum of even harmonic within 10KHz extracted from adjacent current cycle's difference are amplified more than 20 times after arc fault occurs. In the case of serial arc, the discriminant degree of even harmonic characteristic based on the adjacent current cycle's difference is larger than that based on the original data. Therefore, even harmonic power sum within 10kHz can be used as characteristic to distinguish arc from normal conditions under rectifier bridge load, and even-order harmonic power of adjacent cycle's difference can be better used to detect serial arc faults of rectifier bridge load circuits which are difficult to detect.

It can be concluded from Fig 8. that even-harmonic power sum can be used for arc detection in rectifier bridge load circuit. The threshold interval of even harmonic power sum based on adjacent cycle's difference is wider. It performs better when using even harmonic power sum based on adjacent cycle's difference to detect arc fault.

IV. Conclusion

Based on the AC arc experimental platform, this paper studies the arc fault characteristics of rectifier bridge load circuit in AC system. Through experiments and analysis, the following conclusions are drawn:

(1) The current of rectifier bridge load circuit under normal cases exists flat shoulder section. The proportion of flat shoulder section increases after the occurrence of serial arc, and decreases after the occurrence of parallel arc.

(2) When arc faults occur in the rectifier bridge load circuit, the fluctuation of the main circuit current's RMS and DC component is large. The RMS standard deviation and DC component standard deviation based on adjacent cycle's difference increase more than 6 times under different frequency conditions, which is higher than the distinction of time domain characteristic extracted from the original data. They can be used as the characteristic to detect arc faults. The difference between adjacent current cycles effectively enlarges the randomness of arc.

(3) When arc fault occurs in rectifier bridge load circuit, the even harmonic component increases significantly, and the even harmonic power sum of arc extracted from the difference of adjacent current cycles are 20 times larger than that of normal cases. In case of serial arc fault, the discrimination degree of the power sum of even harmonic extracted from adjacent current cycle's difference is higher than that of the original data. The even harmonic power sum of adjacent current cycle's difference can be used as the characteristic for arc fault detection.

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