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Arc Detection System using a Spectrometer for Status Monitoring of a Rigid Catenary

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Abstract – In this paper, a system for the precise detection of arcs is proposed for a rigid catenary using a spectrometer. For this purpose, a miniature rigid catenary contact-loss simulator was used. Experiments were performed by varying the amplitude of the excitation frequency with which a real arc can occur using a simulator in the range of 5 to 15 mm. The range of the radiated wavelength of the copper, which is a material in the rigid catenary, and the irradiance were measured using a spectrometer according to the generated contact loss. In addition, the amount was monitored over time and its characteristics were analyzed. The voltage and current of the load were analyzed when the arc occurred due to contact loss. The analytical results will be applied to detect rigid catenary arcs and used as a monitoring system for real vehicles developed in the future. This will prevent abrasion and disconnection in rigid catenary systems.

Keywords: Rigid catenary, Spectrometer, Contact-loss simulator, Railway, Absolute irradiance

1. Introduction

The speed of high-speed railway vehicles is increasing around the world. In Korea, the High-Speed Electric Multiple Unit (HEMU) railway vehicle system was developed to improve operating speed to 430 km/h [1-2]. The performance of the power collecting system in a high-speed train powered by electricity greatly affects the running and safety of the railway vehicle. The interface between the contact wire that supplies electricity and the pantograph, which is the power-collecting device, is highly important for the running of the railway vehicle. It is important to maintain constant contact between the catenary and the pantograph during railway vehicle operation. However, because of the increase in railway car speed and the route gradient, momentary unstable contact states or opening phenomena occur intermittently. This is called “contact loss.” During contact loss, current flows between the electric line and the pantograph, and an arc discharge accompanied by strong light is generated. The arc generation can be accompanied by various types of performance deterioration, such as the quality of the catenary and the pantograph, aging, abrasion of the catenary, temperature rise, and fatigue fracture [3-5].

Recently, research on arcing due to contact loss has been actively conducted because of the increased operation of high-speed railway vehicles in Korea. Arc discharge detection is a key measure to judge the performance of current collection systems. In arc discharge measurement, the wavelength of the visible light band affects the accuracy of the measured data. It is therefore performed at night or in tunnels because measurement is difficult in areas affected by ambient light. In particular, it is difficult to increase the speed of a rigid catenary system that is currently applied to a tunnel section because of the lack of flexibility. For this purpose, it is necessary to analyze the interface between the rigid catenary and the pantograph by analyzing the arc caused by contact loss. The arc can cause disconnections from the rigid catenary as well as electrical wear [6]. Arc detection technology is required to prevent accidents through monitoring.

In this paper, a system for precise detection of arcs is proposed for a rigid catenary using a spectrometer. For this purpose, a miniature rigid catenary contact-loss simulator was used. Experiments were performed by varying the amplitude of the excitation frequency at which real arcing can occur using a simulator in the range of 5 to 15 mm. The range of the radiated wavelength of the copper, a material in the rigid catenary, was confirmed. The absolute irradiance was measured with a spectrometer according to the generated contact loss. In addition, the amount was monitored over time and its characteristics were analyzed. The voltage and current of the load were analyzed when the arc occurred due to contact loss. The analytical results will be applied to rigid catenary arc detection and monitoring systems for real vehicles developed in the future. This will be used to prevent abrasion and disconnection in rigid catenary systems.

2. Rigid Catenary Contact Loss Arc

Fig. 1 shows a rigid catenary system. The rigid catenary

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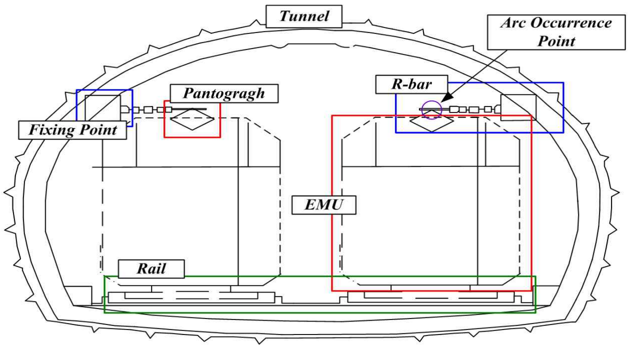


Fig. 1. Rigid catenary system

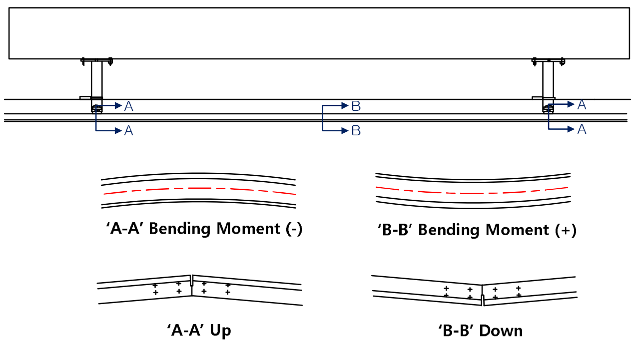


Fig. 2. Bending moment of a rigid catenary system

system consists of rigid lines supported by brackets in limited spaces such as underground areas or tunnels. There is no need for devices such as the tension and curve push devices required in normal catenary methods. In addition, the rigid catenary system is quite simple. However, because the rigid catenary system is less flexible, the wear on the rigid catenary is severe. Therefore, continuous maintenance is required.

Contact loss generally generates an arc with strong light when current flows through the air gap between the rigid catenary and the front plate of the pantograph. Contact loss can be classified as small, medium, or large according to the duration of the momentary gap. However, an arc may occur when the contact surface of the pantograph and rigid catenary is incomplete, despite the absence of an air gap.

2.1 Characteristics of the rigid catenary

The physical and electrical aspects should be explained in order to analyze the characteristics of the rigid catenary system. From the analysis of bending moment, it can be seen that the magnitude and direction of the bending moment act differently according to the position of the R-bar, as shown in Fig. 2. The R-bar acts on the A-A upward moment, and the R-bar bends downward around the B-B.

Fig. 3 shows the deflection of a rigid catenary [8]. In the middle of a rigid catenary, the frequency of arc is high because of the deflection point.

The equation of deflection of a rigid body is

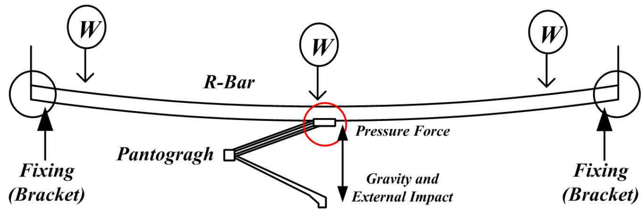


Fig. 3. Deflection of a rigid catenary system

$$v = \frac{w}{24EI}(x^4 - 2Lx^3 + L^3x) \quad (1)$$

where v is the deflection of the rigid catenary, x is an arbitrary length, w is the weight, and EI is the flexural stiffness, and L is the length between fixing points.

Because the copper shoe of a railway vehicle slides, the catenary undergoes deflection or deformation, causing excitation and contact loss of the catenary. The maximum deflection occurs in the middle of the rigid catenary, and its value is equal to

$$\delta = v(\frac{L}{2}) = \frac{5wL^4}{384EI} \quad (2)$$

where δ is the maximum deflection.

As shown in (2), the maximum deflection becomes smaller as the bending stiffness of the rigid catenary increases because of its weight. It can also be seen that deflection increases in proportion to the fourth power of the length. The arc is generated in some of the impacts between the pantograph of the railway vehicle and the catenary. If the speed of the railway vehicle is high, this phenomenon occurs frequently [8]. As a result, arcing occurs because of the deflection phenomenon of the rigid catenary and the external impact of the pantograph and the air resistance.

2.2 Absolute irradiance analysis of contact-loss Arc

In this study, a spectrometer system was used to analyze the arc of a rigid catenary. The system measures the irradiance at the time of arcing. Absolute irradiance is the radiation dose of compound radiation away from the radiation source. Let ΔA be the area element including the point, and $\Delta\varphi_e$ be the radial flux incident on this area. The absolute ΔE_e at that time is given by

$$E_e = \lim_{\Delta A \to 0} \frac{\Delta\varphi_e}{\Delta A} = \frac{d\varphi_e}{dA} \quad [W/m^2] \quad (3)$$

This is the amount of radiation per unit area; it is inversely proportional to area. Because the area has the same unit as the square of the distance, the irradiance is inversely proportional to the square of the distance. Therefore, when arcing occurs, the irradiance is larger when the distance is closer, and closer when the distance is larger. Therefore, the closer the detector is to the light source, the more accurate the measurements of the arc detection device. Furthermore, the arc detector should be sensitive to the wavelength of light emitted by the copper (Cu) material. Therefore, the detector must be sensitive to the copper (Cu) wavelength range of 220 to 225 nm or 323 to 329 nm.

3. Design of a Contact-Loss Simulator for a Rigid Catenary System

In this study, a contact-loss simulator was used for arc generation in a rigid catenary system. The pantograph slides on the catenary in an electric railway vehicle, and vibration occurs according to the excitation frequency in the catenary. The vibration of this simulator was designed to be 0 to 10 Hz[7] in the characteristic frequency of the current collection of the pantograph. The experiment was performed by varying the conditions of the simulator [8]. In addition, the amplitude of the excitation frequency was designed to operate in the range of 5 to 15 mm. Table 1 shows the parameters of the contact-loss simulator for the rigid catenary system. The spring and air compressor were installed to simulate spring constant and uplift force of the pantograph.

Fig. 4 shows the contact-loss arc detection system for the rigid catenary. The contact-loss simulator was used to generate the contact loss, and the arc irradiance was measured using the contact loss arc detection system. The contact-loss arc detection system was used to detect the absolute irradiance of the generated arc [8].

The measurable wavelength range of the contact loss arc detection system was 200 to 1100 nm. A spectrometer is a device that obtains a spectrum by dispersing light. In the simulation, the changing amount of electrons in the metal was estimated using the different reflectance characteristics of the metal surface depending on the wavelength of the ultraviolet rays. The signal transferred through the contact-loss arc detection system was displayed by software according to size and wavelength measured by the data processing interface. The wavelength band that the detection lens could analyze at the detection point was 200 to 1100 nm. The experiment was conducted in a dark room to improve the accuracy of the arc measurement by reducing the effect of ambient light. Fig. 5 shows the configuration of the contact loss-arc detection system.

Fig. 6 shows the instant absolute irradiance waveform displayed in the software during an arc at 2 Hz. The x-axis shows the wavelength (nm), and the y-axis shows the absolute irradiance (μW/ cm^2 /nm).

The wavelength range suggested in EN 50317 is 220 to 225 nm or 323 to 329 nm [9]. As shown in Fig. 6, high values of absolute irradiance were experimentally confirmed at 200 to 225 nm. However, values at 323 to 329 nm were lower than values at 200 to 225 nm. Due to these observatio ns, the sum of the irradiance values in the range

Table 1. Parameters of contact-loss simulator for the rigid catenary system

Content		High-speed railway	Contact-loss simulator
Input voltage		25,000 V	220 V
MCB breaking current		2,000 A	20 A
Maximum capacity of power conversion system		2,600 kW	2.0 kW
R-bar	Material	Aluminum	
	Radius	0.0265 m	

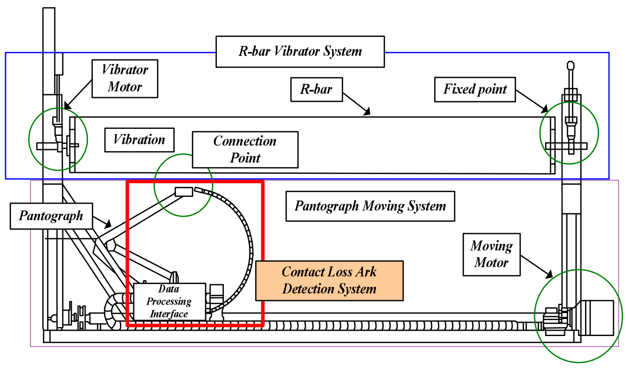


Fig. 4. Contact -loss arc detection system for rigid catenary

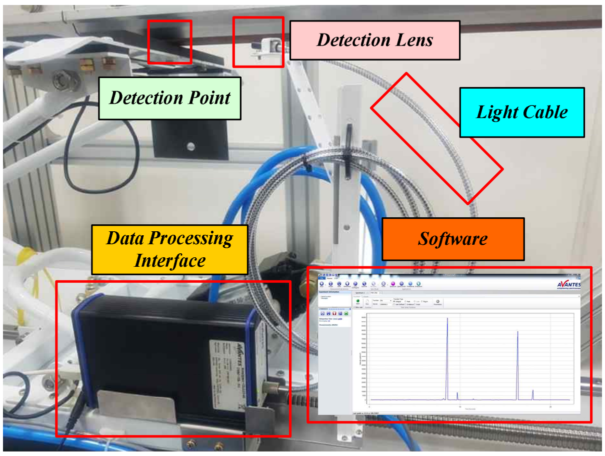


Fig. 5. Schematic of the contact-loss arc detection system

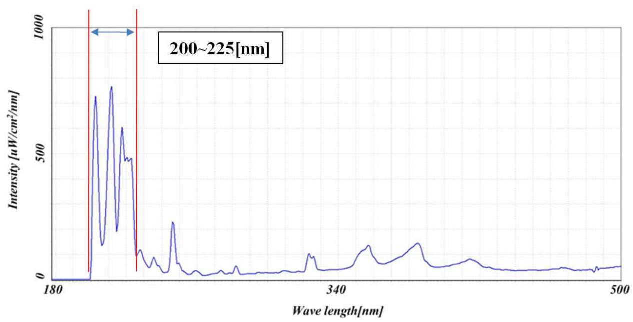


Fig. 6. The instant absolute irradiance waveform displayed by the software during an arc at 2 Hz

200 to 225 nm were measured over time to detect the arc in this study. If the sum of the irradiance values was high, the electric fatigue of rigid catenary was large. The measured value of the irradiance of the rigid catenary arc detection system is shown by

$$D_{Arc} = \int_a^b V_{Irradiance} dw \quad [\mu W/cm^2/nm] \tag{4}$$

where D_{Arc} is the sum of absolute irradiance, $V_{Irradiance}$ is the value of irradiance per wavelength, and w is the wavelength.

4. Experiment of the Contact-Loss Phenomenon using the Rigid Catenary System

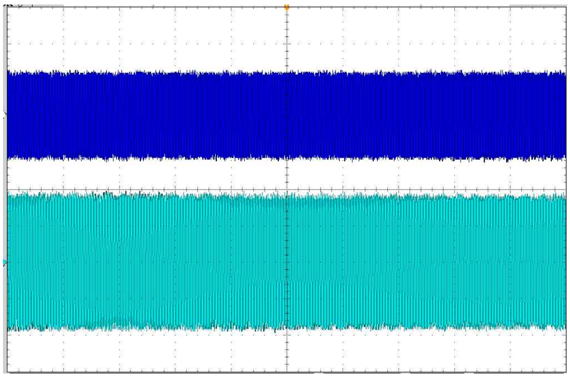
4.1 Analysis of Arc absolute irradiance according to amplitude

In this experiment, voltage and current were analyzed and the absolute irradiance was measured when contact loss occurred. The absolute irradiance was measured as the sum of the range of 200 to 225 nm, the irradiance range of copper (Cu). The irradiance was measured in the range of 323 to 329 nm, but because the numerical value was small, it was judged that the experimental result would not be greatly affected. To increase the recording speed, the absolute irradiance was measured as the sum of the range of 200 to 225 nm. Experiments were carried out by changing the amplitude of the excitation frequency of the rigid catenary using the miniature contact-loss simulator. Fig. 7 shows a graph of voltage and current for an excitation frequency of 2 Hz and an amplitude of 5 mm. As shown in Fig. 7(a), the voltage and the current flow well without a zero point where the contact loss is not generated in the case of 5-mm amplitude. Fig. 7(b) shows an enlarged waveform of Fig. 7(a); the wave appears in sinusoidal form.

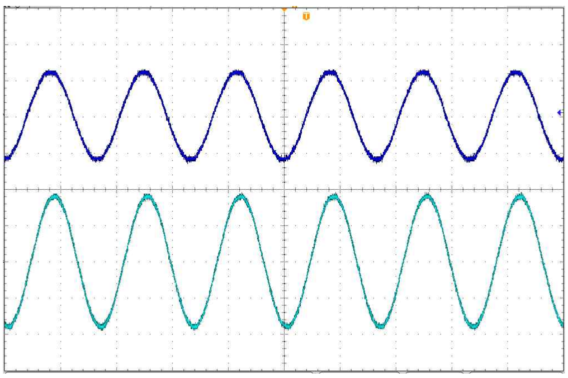
Fig. 8 shows the absolute irradiance under the same conditions as those in Fig. 7. Arcs due to incomplete contact can be confirmed even though the voltage and current waveform cannot confirm the occurrence of contact loss from the distortion of the waveform. The arc can be seen to output different absolute irradiance values depending on the pantograph tracking and rigid catenary conditions. The maximum absolute irradiance was approximately 94,510 $\mu W/cm^2/nm$, and irradiances over 40,000 $\mu W/cm^2/nm$ occurred twice in 20 s.

Fig. 9 shows the voltage and current waveforms when the excitation frequency is 2 Hz and the amplitude is 10 mm. Fig. 9(a) shows that the point where the voltage and the current become zero occurs because of the contact loss in the condition of 10-mm amplitude. Fig. 9(b) shows a waveform that enlarges the point where the contact loss is the longest. In addition, it can be seen that the waveform at this point is highly distorted.

Fig. 10 shows the absolute irradiance under the same conditions as those in Fig. 9. The generation of the contact loss in the voltage and current waveforms was confirmed. In addition, the arc generation could be confirmed. The arc can be seen to output different absolute irradiance values depending on the pantograph tracking and rigid catenary

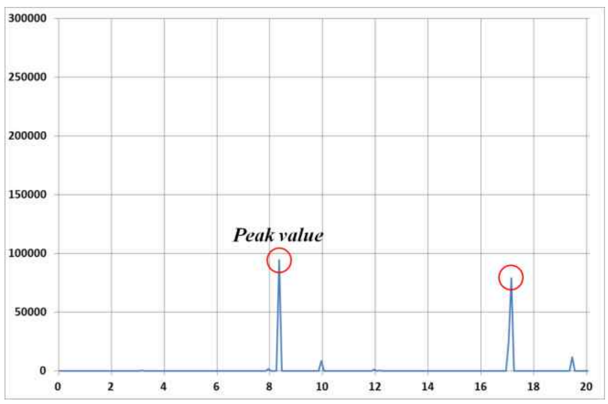


(a) Time division (x-axis): 2 s



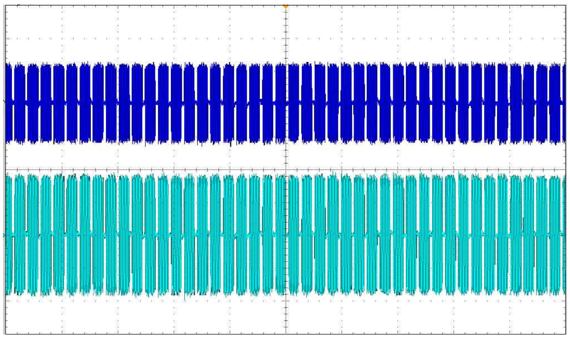
(b) Time division (x-axis): 10 ms

Fig. 7. Voltage and current waveforms in the condition of 2 Hz, 5 mm (Y axis: 250 V/div., 10 A/div.)

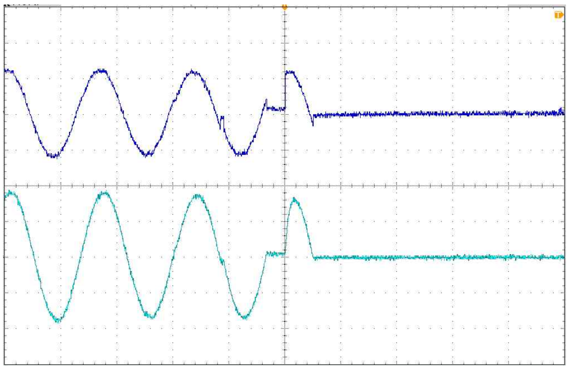


(X axis: time [s], Y axis: absolute irradiance [$\mu W/cm^2/nm$])

Fig. 8. Absolute irradiance waveforms for 2 Hz, 5 mm

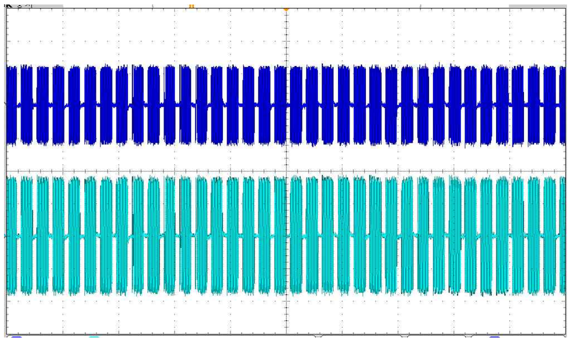


(a) Time division (x-axis): 2 s

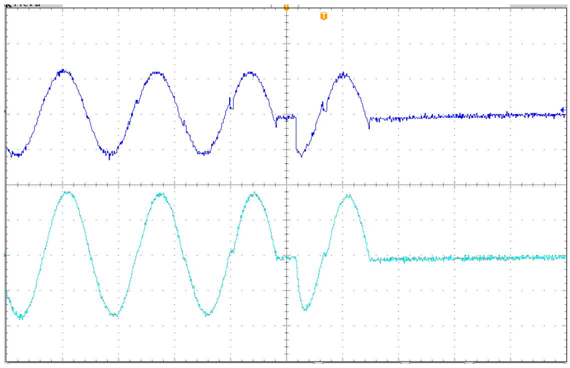


(b) Time division (x-axis): 10 ms

Fig. 9. Voltage and current waveforms in the condition of 2 Hz, 10 mm (Y axis: 250 V/div., 10 A/div.)

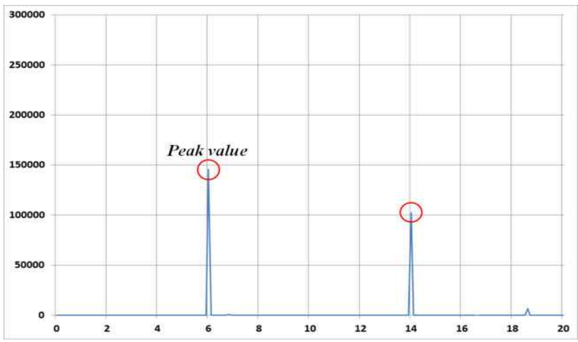


(a) Time division (x-axis): 2 s



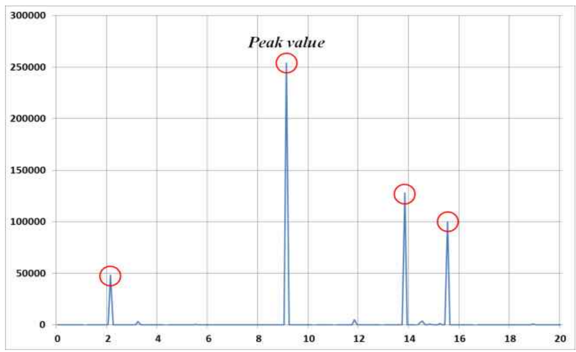
(b) Time division (x-axis): 10 ms

Fig. 11. Voltage and current waveforms in the condition of 2 Hz-15 mm (Y axis: 250 V/div., 10 A/div.)



(X axis: time [s], Y axis: absolute irradiance [μW/cm^2/nm])

Fig. 10. Absolute irradiance waveforms for 2 Hz, 10 mm



(X axis: time [s], Y axis: absolute irradiance [μW/cm^2/nm])

Fig. 12. Absolute irradiance waveforms for 2 Hz, 15 mm

conditions. The maximum absolute irradiance was approximately 145,748 μW/cm^2/nm, and irradiances over 40,000 μW/cm^2/nm occurred twice in 20 s. Compared with the 5-mm condition, it was confirmed that there is no significant difference in the number of arc occurrences. However, it was confirmed that the difference in the peak value of the absolute irradiance was approximately 50,000 μW/cm^2/nm.

Fig. 11 shows the voltage and current waveforms when the excitation frequency is 2 Hz and the amplitude is 15 mm. As shown in Fig. 11(a), the point where the voltage and the current become zero occurs because of the contact loss in the conditions of 10-mm amplitude. Fig. 11(b) is a waveform that enlarges the point where the contact loss is the longest. It can be confirmed that the distortion of the waveform was the most severe among all of the tested amplitude conditions.

Fig. 12 shows the absolute irradiance under the same conditions as those in Fig. 11. The generation of the contact loss in the voltage and current waveforms was confirmed. In addition, arc generation could be confirmed. The arc can be seen to have outputted different absolute irradiance values depending on the pantograph tracking and rigid catenary conditions. The maximum absolute irradiance was approximately 254,149 μW/ cm^2 /nm, and irradiances over 40,000 μW/ cm^2 /nm occurred four times in 20 s. Compared with the 10-mm amplitude condition, it was confirmed that the number of arc occurrences increased. In addition, it was confirmed that the difference in the peak value of the absolute irradiance was approximately 100,000 μW/ cm^2 /nm.

4.2 Analysis of experimental results

In this study, the arc of a rigid catenary was analyzed through an arc detection system using a spectrometer. Our research has shown that even if the voltage and current are not completely disconnected, an arc can occur if the contact between the pantograph and the rigid catenary is incomplete. In addition, it was confirmed that the number of occurrences of arcing and the size of irradiance vary with the amplitude and the condition. Table 2 shows the data of the arc detection experiment according to the amplitude. As a result of this analysis, it was confirmed that more arcs were generated at 15 mm than at 5 or 10 mm. As the amplitude increases from 5 mm to 15 mm, the maximum value of the arc's absolute irradiance increases.

Fig. 13 shows the peak absolute irradiance waveforms at the 2-Hz, 15-mm conditions. The experiment was repeated approximately 50 times under the same conditions. The outputted values were not always constant. However, the overall trend was confirmed. The detection system can detect arcs over time, and the railway vehicle has records of location information. Combining this information allows the location of rigid catenary fatigue to be predicted. According to this information, preventative maintenance can be performed to avoid accidents caused by dis-connection and abrasion. The arc was shown to occur even if there was no distortion of the waveform. Therefore, the arc cannot be measured by conventional methods, which monitor voltage and current.

Table 2. Experimental data of arc detection according to amplitude

Amplitude [mm]	5	10	15
Number of absolute irradiance over 40,000 within 20 s	2	2	4
Peak absolute irradiance [μW/cm^2/nm]	94,510	145,748	254,149

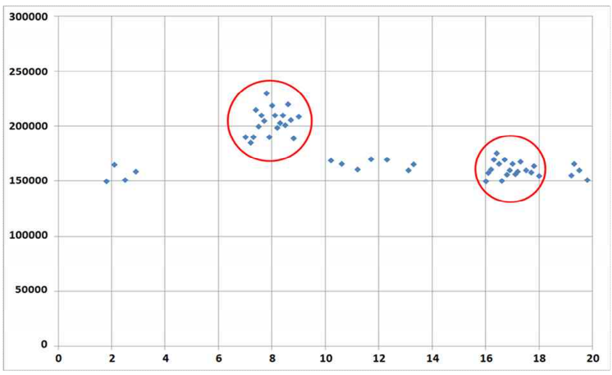


Fig. 13. Peak irradiance waveforms for 2 Hz-15 mm

5. Conclusion

This paper proposes an arc detection system based on a spectrometer and presents the analysis of the arcs that occur during contact loss in a rigid catenary. The results of the study are as follows:

(1) Distortion of voltage and current occurred when a contact loss occurred. However, the arc did not always occur whenever distortion occurred. Therefore, the arc cannot be measured using conventional methods that monitor voltage and current. (2) In addition, it can be confirmed that the number of arc occurrences varies according to the amplitude condition. Large or small arcs continue to occur when the contact between the pantograph and the rigid catenary is incomplete or disconnected. As a result of this analysis, it was confirmed that more arcs were generated at 15 mm than at 5 or 10 mm. Furthermore, as the amplitude increases from 5 mm to 15 mm, the maximum value of the arc's absolute irradiance increases. (3) The reliability of the arc detection system was verified through several experiments. (4) Use of this system allows prediction of the fatigue of rigid catenary. According to this information, maintenance can be performed in advance to prevent accidents caused by disconnection and abrasion.

These analytical results will be applied to the arc detection and monitoring systems for the rigid catenaries of vehicles developed in the future.

Acknowledgements

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