Design and Simulation for Optical Acquisition of Pantograph-catenary Arcing Detection System of Electrified Railway

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Abstract. Running efficiency of electrified railway is restricted seriously by arcing between pantograph and overhead line system. Since the frequency of arcing happens can reflect the contact-loss rate between pantograph and catenary system, the qualitative determination of arcing plays a more and more important role in this professional field. Detection system based on ultraviolet ray in sunlight blind region can detect time, location and amplitude of arcing. To design a reasonable optical system can collect optical signal maximally of a feeble ultraviolet ray of arcing and it is useful to increase the detection accuracy. Photon number collecting by fiber bundle of optical gather system on the top of the train is estimated when it is installed 3 m distance from the contact point between pantograph and contact line. And the image spot size is simulated in this paper. The results indicate that sizes of image spots are similar to the airy spots, so the light energy lost can be neglected when coupling. The parameters designed for optical system in this paper meet the requirement of photon acquisition.

1. Introduction
With the rapid development of urban rail transit, as one of the three most important relationships of railway, the relationship of pantograph and catenary system attracts more and more attention. Arcing is the important indexes to measure whether the relationship of the pantograph and catenary system is normal. The hazards of arcing mainly include abnormal abrasion, possible rupture, serious ablation, poor stability of the current between carbon strip and contact line, and it results in electromagnetic interference to nearby communication lines, even cause power outages [1]. Therefore, it is necessary to find a method to detect the arcing in real-time.

The main features of arcing between pantograph and catenary system are thermal, optical, electromagnetic and acoustic characteristics. According to different characteristics, different arcing detection methods have appeared successively, but each method has its limitations [2,3]. So a new detection method based on solar blind with its optical acquisition system installed on the roof of the train and photoelectric sensor in the control room of the train is proposed in this paper, which can avoid the interference of high-voltage electromagnetic of the photoelectric sensor module effectively.

2. Materials and methods
Detection system of pantograph-catenary arcing. The arcing detection system is composed of optical acquisition system, ultraviolet photoelectric sensor module and data processing module. Figure 1 shows the structure of the detection system. The whole system is divided into two parts in space, the
optical acquisition system and optical fiber are installed on the roof of the train, the ultraviolet photoelectric sensor and data processing module in the control room of the train. When arcing occurs, it can be imaged at the end of the optical system through a narrow-band filter. Only ultraviolet light distributed in 280±5 wavelength range can pass through the filter. The optical signal is transmitted to the photoelectric sensor by ultraviolet fiber. The ultraviolet photon is converted into impulse current signal after passing through the photoelectric sensor, amplifying, maintaining and sampling circuit, the pulsed current signal obtained by the data processing unit is processed accordingly to obtain the current signal which is proportional to the arcing intensity. Meanwhile, GPRS is used to obtain position data of the locomotive operation when arcing occurs, and the dates are stored for interface display and post-processing.

The key to arcing detection system is how to collect effective optical signal maximally and transfer the signal to the photoelectric sensor module and converted it into usable electrical signal, for processing and analyzing. Therefore, to design a reasonable optical acquisition system is very important to improve the accuracy of the arcing detection system.

**Parameters design for optical system.** The optical acquisition system is fixed on the roof of the train by a pedestal, and it can be adjusted to make the lens aim at the contact point of the arcing occurrence point, the optical acquisition system and the photoelectric sensor is connected by optical fiber as is shown in figure 2. The target of the design is to image the arcing (Φ400mm) between pantograph and catenary system to the fiber end face (Φ2.5mm) by the optical imaging system. The optical parameters of the imaging system are designed 3 m distance between arcing occurrence position and the optical system.

The optical parameters are calculated when the imaging lens is considered as ideal. The initial
conditions for the optical system can be obtained according to the designed target above, diameter of the object surface is 400 mm, the object distance is 3m, diameter of the image plane is 2.5mm, coupling angle of the optical fiber end face is 25°, so the numerical aperture (NA) of the imaging system is

\[ NA = \sin \left( \frac{25°}{2} \right) = 0.22 \]  

(1)
light beam larger than this numerical aperture size cannot be coupled into the fiber. The magnification of the imaging system can be obtained by simulating with ideal lens.

\[ \beta = \frac{400}{2.5} = 160 \]  

(2)
The image distance, focal length and optical aperture can be calculated by the follow formula. The calculate results are shown in table 1.

\[ v = \frac{u}{\beta} \]  

(3)
\[ \frac{1}{f} = \frac{1}{u} + \frac{1}{v} \]  

(4)
\[ f = D \times NA \]  

(5)
In the formulas above, \( v \) is the image distance, \( u \) is object distance and \( f \) is the focal length. \( D \) is the effective relative aperture of the lens.

| U(m) | V(mm) | F(mm) | D(mm) | Photon number of single optical fiber | Photon number of fiber optical bundle |
|------|-------|-------|-------|--------------------------------------|--------------------------------------|
| 3    | 18.75 | 18.6335 | 8.4  | 278                                 | 19615                                |

**Evaluation of photon collection effect.** Arcing spectrum experiment was done in a dark room environment with a spectrum analyzer before, the results showed that, when a single fiber whose core diameter was 1mm placed at the distance of 2.5 m from the ultraviolet light-emitting objects, the analyzer could collect 400 photons per second. Based on the experimental results, the number of photons collected under the three distance schemes can be estimated.

When the imaging lens is equivalent to an ideal, it is necessary to consider that the number of receiving photons would be influenced by optical fiber arrays gaps in the fiber bundle, the attenuation of the photons in the transmission process and the surface reflection of the lens.

(1) Photons number received by a single fiber under three range schemes in the ideal case.

Since the power function relation is satisfied between the effective number of photons and the observed distance, and the average value of the power function is 2 in the ideal case, the following relation is satisfied:

\[ g_{dx} = g_d \left( \frac{d}{d_x} \right)^2 \]  

(6)
In the formula, \( g_{dx} \) represents the number of photons received by the optical fiber at the position to be measured, \( g_d \) denotes the number of photons received by the optical fiber under the experimental distance, \( d \) is the experimental distance and \( dx \) is the distance to be measured.

It can be estimated by the formula above that, if the single fiber is placed 3m distance from the lighting object, the number of photons received by spectrum analyze is 278.

(2) The number of photons received after passing through the optical imaging system.

When the distances is 3m, the effective optical aperture of the optical system is 8.4mm, so its area is \( 8.4^2 = 70.56 \) times than single fiber, as a result, the number of photons received by the optical system is \( 70.56 \times 278 = 19615 \).

(3) Optical fiber arrays gaps in the fiber bundle

The receiving surface is considered as round \( \Phi 2.5 \) mm and assume that there is no gap in the optical fiber array in the calculation above, but actually there are small gaps between each optical fiber in the bundle. Therefore, the estimated result should be multiplied by the scale factor of the area. As the fiber bundle is composed of 100 fibers and the core diameter of each fiber is 200μm, so the area proportion factor is \( 100 \times \pi \times 0.1^2 \times 1.25^2 = 0.64 \).

(4) Consider filter attenuation and reflection of the lens surface.
The results are obtained without considering the attenuation of photons in the transmission process and mirror reflection of the lens, but in reality, the transmittance of the filter can reach at least 70%. When coated with the anti-reflection film, the transmittance of each piece of optical filter can reach more than 99%. This optical system uses four lenses and one protective window. Therefore, the overall transmittance of the lens group is 99%×5 = 95%. In summary, the final estimated value of photons number collected by the system is $N = 19600 \times 70\% \times 95\% \times 64\% = 8348$.

It is worth noting that this estimate is based on the results of laboratory experiment previously. If the intensity of the arcing change, the number of photons collected will change in equal proportion. Photocell sensor is very sensitive to faint light. The more the number of photons collected, the more accurate the arcing intensity can be reflected, and the interference effects such as cosmic rays can be avoided successfully.

**Simulations of image points size.** Due to the wave nature of light, it will be diffracted through a small hole, and resulting in the pattern of light and dark fringe diffraction, the spacing of the stripes will increase with the reduction of the size of small holes, at the central area of the diffraction pattern there is the largest bright spot, known as airy spot.

The geometric radius of the image refers to the radius of the image area formed by the light rays passing through the lens. The optical system can be considered ideal if the dimensions of each point on object surface are similar to the airy plot. The image size and airy spots of the object surface center (OBJ-0mm), 100mm (OBJ -100mm) and 200mm (OBJ -200mm) from the object surface center under the 3m distance scheme were respectively simulated. The results are as follows in figure 3.

![Simulation results of image point at the center and edge of object plane](image)

3. **Results and discussion**

The radiation spectrum of the sun covers the entire spectrum from x-rays to radio waves, the vacuum ultraviolet (100-200nm) is absorbed by atmospheric oxygen ion, the medium ultraviolet radiation (200-300nm) is absorbed by ozone in the stratosphere. So the ultraviolet distribute between 100-300nm almost non-existent in the atmosphere [4], as is known as the "solar blind area". As a result, only near ultraviolet (300-400nm) radiation can reach the surface of earth.

With the phenomenon of arcing, the electrons or ions of certain materials will be generated with a certain wavelength in the process of transition from a high energy level to the low [5]. The essence of arcing is the final manifestation of gas discharge, during which ultraviolet radiation will be emitted with the light effect [6]. The arcing spectrum covers ultraviolet, infrared and visible light, because the waveband of 280±5 nm is included of the solar blind area, and it can hardly be found on the surface of the earth. So it can be used as the characteristic wavelength of ultraviolet light for arcing detection because of avoiding the interference from sunlight effectively, and the detect result of arcing phenomenon would be more accurate.

The results of multiple spectrum experiments show that the distribution of characteristic ultraviolet light in arcing spectrum is basically constant. Therefore, in ideal conditions, it can be inferred that the proportion of the characteristic ultraviolet radiation energy is certain of the total energy of arcing [7]. Therefore, the detection results of ultraviolet light at the feature waveband can directly reflect the strength of pantograph-catenary arcing.

This detection system based on solar blind with its optical acquisition system installed on the roof of the train and photoelectric sensor in the train room, it is different from Japan and Italy, whose...
electromagnetic interference is serious and detection accuracy is low due to their photovoltaic sensor installed on the roof of the train, so close to the high-voltage contact line. So it can avoid the interference of high-voltage electromagnetic of the photovoltaic sensor module effectively.

The calculation results show that the designed optical acquisition system can receive 8348 photons per second at the time of arcing occurrence after fully considered the optical beam gap and attenuation by the lens, there are enough photons to drive the photovoltaic sensor can convert the optical signal into electric signal and reflect the strength and duration of arcing accurately.

It can be seen from the simulation results the airy spot radius of the imaging system is 0.791mm, and the image point radius of OBJ-0mm is 0.486 mm, significantly smaller than the airy spot, the size of OBJ-100mm and OBJ-200mm image points are slightly larger than airy spot. Therefore, it can be considered that the image point size is similar to the airy spot. Although the arcing edge is slightly lost in the imaging process, it does not affect the qualitative judgment of the arcing detection system. The results show that the optical system can meet the acquisition requirements of arcing.

4. Conclusions
The real-time online arcing detection system based on ultraviolet light can provide a certain basis for the performance evaluation and maintenance of the pantograph-catenary system. To design a reasonable optical acquisition system on the roof of the train is useful for collecting the arcing ultraviolet characteristic band light signals maximum, and reflect the arcing duration and strength information accurately. The optical system designed in this paper can meet the requirements of arcing photon acquisition, transmit arcing information of the pantograph-catenary system to the photovoltaic sensor and subsequent modules for processing. In practical application, the parameters of optical lens should be selected according the distance between point of arcing occurrence and the position of optical acquisition system. This design can provide theoretical basis and design idea for further research in related fields.

Acknowledgements
This work is financially supported by the Youth Fundation of Lanzhou JiaoTong University (2015038). The project name is prediction technology of thickness and type of ice on electrified railway contact line.

References
[1] Z. Gao, G. Wu, W. Lv, C. He, L Zhou. Research review of arc phenomenon between pantograph and catenary in high-speed electric railway. High Voltage Apparatus, 45 (3): 104-108. (2009)
[2] T. Hayasaka, M. Shimizu, K. Nezu. Development of Contact-Loss Measuring System Using Ultraviolet Ray Detection. Quarterly Report of RITI, 50 (3): 131-136. (2009)
[3] O. Bruno, A. Landi, M. Papi, L Sani. Phototube Sensor for Monitoring the Quality of Current Collection on Over Head Electrified Railway. Proc. Instn Mech. Engrs, Part F, Journal of Rail and Rapid Transit, 215: 231-241. (2001)
[4] Z. He, X. Chen, X. Zhang. Design of solar blind ultraviolet detection system. Machinery and Electronics, 34 (3): 46-49. (2016)
[5] B. Liu, T. Chen, L. Yu, W Pu. Pantograph-catenary arc energy detection and analysis on current disturbance in metro. Journal of The China Railway Society, 37 (3): 8-13. (2015)
[6] J. Wang, W. Lin, Z. Wang, J Li, W He, P Wang. Online detecting device for switchgear arc based on ultraviolet detection. Power System Protection and Control, 39 (5): 128-133. (2011)
[7] C. Ma, T. Cheng. Analysis the quality of current collection of pantograph-catenary system based on detection of ultraviolet arcing. Southwest Jiaotong University, 7-15. (2013)