

Study on Evaluation Method of Insulator Surface Contamination Level Based on LIBS Technology and PCA Algorithm

Yifan Liao^{1,2}, Yuansheng Li³, Fuzeng Zhang¹, Xueqin Zhang³, Tingting Wang¹, Yujun Guo³,
Zhang Xiao³, Yaozhen Wang³

1. Electric Power Research Institute, China Southern Power Grid Co., Ltd., Guangzhou, China

2. School of Electric Power, South China University of Technology, Guangzhou, China

3. School of Electrical Engineering, Southwest Jiaotong University, Chengdu, China

Abstract- As one of the most important external insulation equipment in power system, insulators play an important role in transmission and distribution network. In this paper, qualitatively and quantitatively analysis of the contaminated elements on the surface of artificial contaminated insulators and natural contaminated insulators were carried out by Laser-Induced Breakdown Spectroscopy (LIBS). For artificial contaminated insulators, Na and Al elements can be used to characterize the equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD) levels respectively. For natural contaminated insulators, there are differences in spectral intensity of contaminated elements with different contamination years. And with the increase of the contamination years, the spectral intensity of the Si, Fe, Ca, Al, K and Na elements also have an increasing trend. Insulator samples under 4 contamination levels were classified based on the principal component analysis (PCA) algorithm. Dimension reduction analysis was conducted by extracting 6 excitation spectra (Si, Fe, Ca, Al, K, Na) which can represent contamination information. The 2 principal components with the largest contribution rate were obtained and the principal component scores of each spectrum were calculated. The research results showed that the spectral sample points have obvious convergence phenomenon according to the contamination level of the insulators. Compared with the commonly used methods for judging contamination level, LIBS technology has the advantages of easy operation, no sample processing and high sensitivity. Therefore, the combination of LIBS technology and PCA algorithm can save time and cost and improve the detection efficiency in the field of insulator contamination monitoring.

Keywords: insulator, contamination level, laser-induced breakdown spectroscopy, PCA algorithm

I. INTRODUCTION

As one of the most important external insulation devices for power system, insulators play an important role in the transmission and distribution networks. With the development of China, the environmental pollution caused by the daily activities of industry and humans is also increasing. The contamination on insulator surfaces will affect its external insulation performance. In severe cases, it will cause flashover, and the flashover on transmission lines will cause large-scale power outage, which will result in power system

failure and bring huge economic losses [1]. Therefore, the evaluation of insulator contamination is the basic research work in the field of external insulation of power systems, which is of great significance for the design, operation and maintenance of external insulation of power systems.

A large number of scholars at home and abroad have conducted a lot of research on insulator contamination detection and achieved a series of outstanding results, which have greatly reducing the power system failure caused by contamination flashover [2,3]. At present, the most common method of measuring contamination is to remove the insulator from the power line and then determine the contamination level by measuring the equivalent salt deposit density and non-soluble deposit density [4]. However, this method is complicated in operation and needs to be powered off, which is not convenient in practical operation [5]. Reference [6] installed metal electrodes on the surface of insulators, which can determine the contamination degree of insulators by measuring the surface conductivity of insulators when the air humidity is relatively saturated. The ultraviolet discharge pulse signal will appear when the leakage current is generated on the insulator surface. The relevant characteristics of the leakage current can be obtained and the contamination degree can be determined by analyzing the signal with a certain algorithm [7]. However, the exact relationship between the current leakage current and the degree of contamination has not been fully clarified, and the installation of the equipment is also complicated, and the degree of environmental impact is relatively large.

In recent years, laser-induced spectroscopy material analysis technology has developed rapidly. It has the characteristics of small damage to materials, long-distance detection, high sensitivity, and real-time detection of suspended particles in solids, liquids and gases. Xie Chengli of Huazhong University of Science and Technology used LIBS calibration technology to analyze metal elements and Si elements in coal and achieved high precision. And the calibration precision of other main elements(C, H, O, N) in coal were improved by using neural network method [8]. Wang Zhihong of Beijing Jiaotong University designed and built the LIBS experimental platform. The optimum experimental conditions of LIBS for sample analysis were studied, and the optimum detection lines of some elements were determined. Then the quantitative

analysis of elements by internal calibration method was explored [9].

Based on laser induced breakdown spectroscopy system, the ultra 100 pulsed laser was used to bombard artificial contaminated insulator sheets and natural contaminated insulators in different contamination levels. The SR-500i spectrometer and ICCD camera were used to collect the emission spectrum during plasma cooling at the laser bombardment. Combining with NIST spectral line database, the peak of spectral line was searched to determine the element types, and qualitatively and quantitatively analysis of the artificial and natural contamination of different contamination grades were carried out. Finally, the PCA algorithm was used to classify and evaluate the natural contaminated insulators.

II. EXPERIMENT

A. The LIBS System

Plasma will be produced on the surface of the insulator sample when the LIBS system uses a high-energy pulsed laser to bombard the sample. The spectra emitted during plasma cooling are collected by a photoreceptor and a spectrometer. Then, the element types on the sample surfaces are determined by the corresponding relationship between the wavelength of atomic spectrum and ion spectrum and the element types in NIST database. And when the concentration of the analyzed elements is low and the phenomenon of self-absorption is not obvious, it is considered that the intensity of the spectral line is proportional to the content of the elements, which can be described by the formula (1).

$$I = aC \quad (1)$$

where I is the spectral line intensity of the element, a is the self-absorption coefficient, C is the element concentration [10].

The schematic diagram of the LIBS device for this experiment is shown in Figure 1. Ultra-100 laser optical system, SR-750-A spectrometer and iStar ICCD Detector are the main equipment used in the experiment. Among them, the working wavelength of the pulse laser is 1064 nm, the pulse width is 8ns, the repetition frequency is 20Hz, and the maximum single pulse energy is 100 mJ. The pixel of ICCD detector is 1024 pixel \times 1024 pixel, and the response wavelength ranges from 120-1100 nm. In the experiment, the laser beam is focused on the surface of the insulator sample by a plano-convex quartz lens with a focal length of 100 nm to generate plasma. The emission spectrum of the plasma is collected by a collection device consisting of a 75 mm plano-convex quartz lens and a 30mm biconvex quartz lens, and the distance between the two lenses is 70 mm. The coupling device couples the spectral signal to the optical fiber and transmits it to the spectrometer through the optical fiber for splitting, and then, the signal will be received and detected by the ICCD detector. The sample is attached to the stage and the plasma image is taken by the ICCD camera with a macro lens (Nikon AF60mm/2.8D).

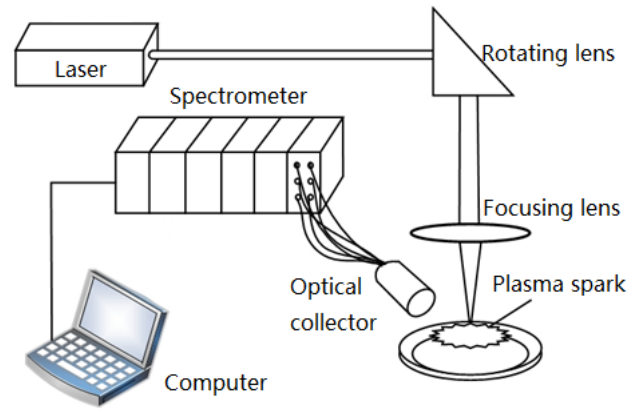


Fig.1 Schematic diagram of the LIBS system

B. Sample Preparation

The experimental samples were selected from two types of artificial contaminated insulation sheets with different contamination levels and four types of insulators with different contamination years. The size of the artificial contaminated silicone rubber insulation sheet is 10cm \times 10cm. The cut silicone rubber insulator is cleaned by alcohol first, and then NaCl and kaolin are used to prepare artificial contaminant turbid liquid and smear it evenly on the clean insulating sheet. According to the above steps, samples 1 with equivalent salt deposit density and non-soluble deposit density of 0.2 mg/cm² and 4 mg/cm² respectively was obtained, while the equivalent salt deposit density and non-soluble deposit density on the surface of sample 2 was 0.5 mg/cm² and 4 mg/cm² respectively, the non-soluble deposit density of sample 2 is the same as sample 1. Natural contaminated samples are the test samples of a railway bureau line, the contamination years are 0.5 a, 1.0 a, 1.5 a and 2.5 a respectively. In order to reduce the influence of non-uniform contamination on the spectral information of samples, five groups of data were collected from different parts of each sample, and the average value was taken as the analysis data.

TABLE I
SAMPLES IN THE EXPERIMENT

Sample No.	Detailed Information
1	Artificial contaminated insulation sheet Equivalent salt deposit density: 0.2 mg/cm ² Non-soluble deposit density: 4 mg/cm ²
2	Artificial contaminated insulation sheet Equivalent salt deposit density: 0.5 mg/cm ² Non-soluble deposit density: 4 mg/cm ²
3	Natural contaminated insulator Contamination year: 0.5 a
4	Natural contaminated insulator Contamination year: 1.0 a
5	Natural contaminated insulator Contamination year: 1.5 a
6	Natural contaminated insulator Contamination year: 2.5 a

III. ANALYSIS OF EXPERIMENTAL RESULTS

A. Analysis of Contamination of Artificial Contaminated Insulators

In the process of artificial smearing, the raw materials for artificial contamination are salt (The main ingredient is NaCl) and kaolin (The main ingredient is Al₂O₃). Therefore, in the process of quantitative analysis, the Na element and the Al element intensity are used to approximate the content of NaCl and Al₂O₃, which means the strength of the Na element and the Al element are used to characterize the equivalent salt deposit density value and the non-soluble deposit density value. The spectra of artificial contaminated samples in the wavelength range of 200-800 nm were observed in the experiment. It is found that Na and Al have obvious absorption peaks, and the relatively strong spectral lines of Na and Al occur at 580-600 nm and 390-400 nm respectively. So the spectral information of the two wave bands was analyzed.

The spectrum of artificial contaminated insulation sheet in 580-600 nm wave band is shown in Fig. 2. Fig. 3 is the intensity comparison of the Na element at 588.78nm and 589.50 nm on the surface of two samples. It can be seen from Fig.3 that the intensity of the Na element increases by 327.57% and 402.05% at two excited states of 588.84 nm and 589.44 nm respectively when the equivalent salt deposit density increases from 0.2 mg/cm² to 0.5 mg/cm². It shows that LIBS system can effectively judge the artificial contaminated insulation sheets under different equivalent salt deposit density.

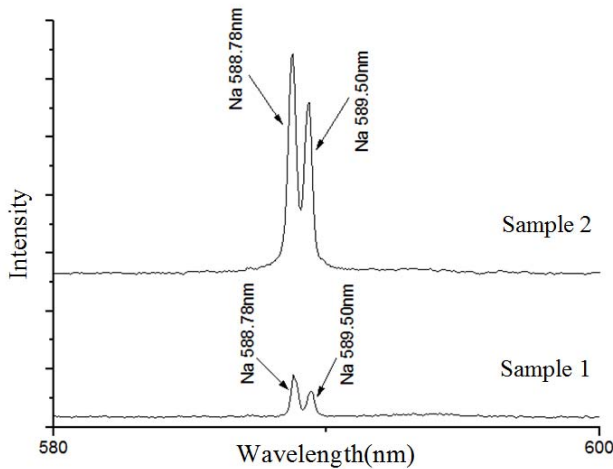


Fig.2 Emission spectra of artificial contaminated sample in 580-600 nm wavelength

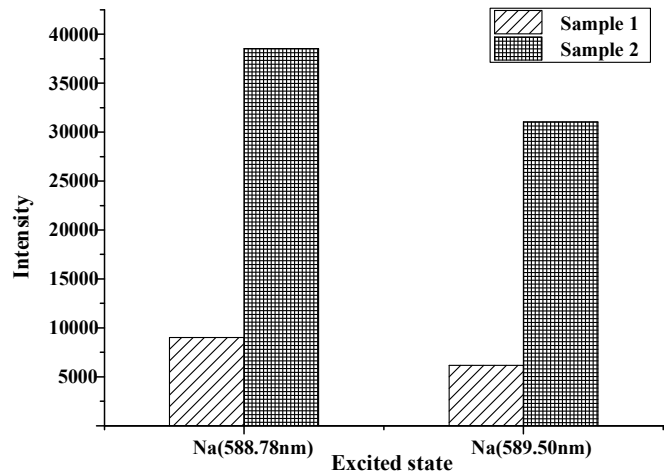


Fig.3 Comparison of Na excited state intensity in different artificial contaminated sample

The spectrum of artificial contaminated insulation sheet in 390-400 nm wavelength is shown in Fig.4. Fig.5 shows the intensity comparison of the Al element at 394.47 nm and 396.21 nm on the surface of two samples. It can be seen that the intensity changes of the Al element which characterizes the non-soluble deposit density are 16% and 23.3% at two excited states of 394.47 nm and 396.21 nm when the non-soluble deposit density value is constant. Compared to the Na element, the change is small.

Through the above analysis, it can be concluded that the information of artificial contaminated element content is positively correlated with the corresponding LIBS spectral intensity, and it is confirmed that the level of artificial contamination can be evaluated based on the intensity of the LIBS line of the contaminated element. Compared with the artificial contamination component, the natural contamination is complicated, and the evaluation error of the contamination level based on a single element is large, so further analysis is needed.

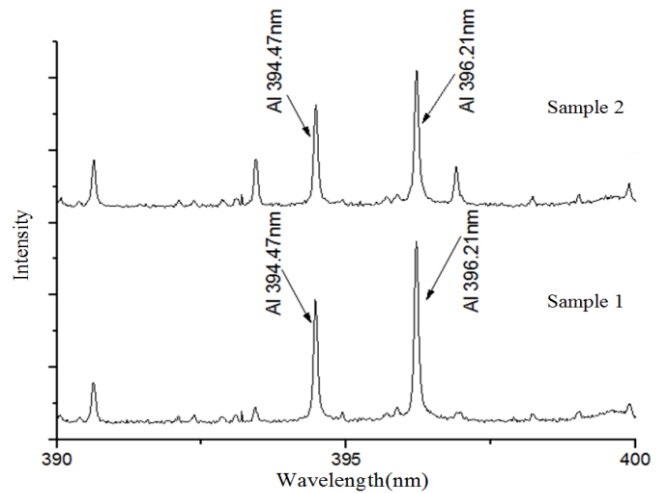


Fig.4 Emission spectra of artificial contaminated sample in 390-400 nm wavelength

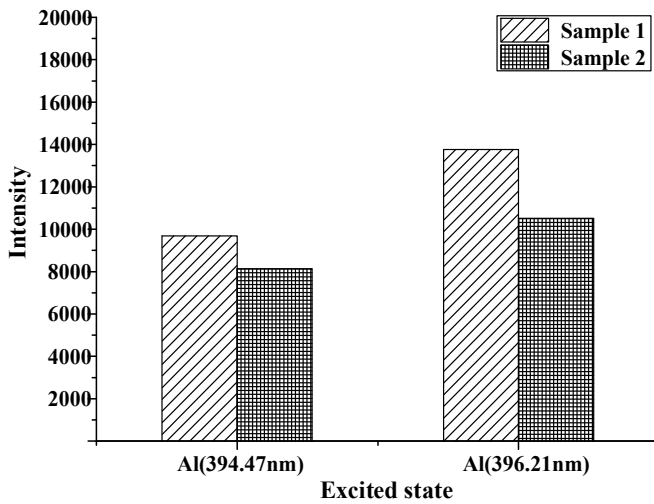


Fig.5 Comparison of Al excited state intensity in different artificial contaminated sample

B. Analysis of Contamination of Natural Contaminated Insulators

In order to study the natural contamination characteristics of outdoor insulators, the surface contamination of four kinds of insulators with different contamination years was tested based on LIBS in this paper, and qualitatively and quantitatively analysis of the research results were carried out. The plasma emission spectrogram of the insulator with a contamination year of 1.5 a is shown in Fig.6. The elements corresponding to the characteristic peaks in the spectrogram can be identified according to the NIST database. It can be seen from the spectrogram that the natural contamination elements are mainly consist of Si, Fe, Ca, Al, K, and Na.

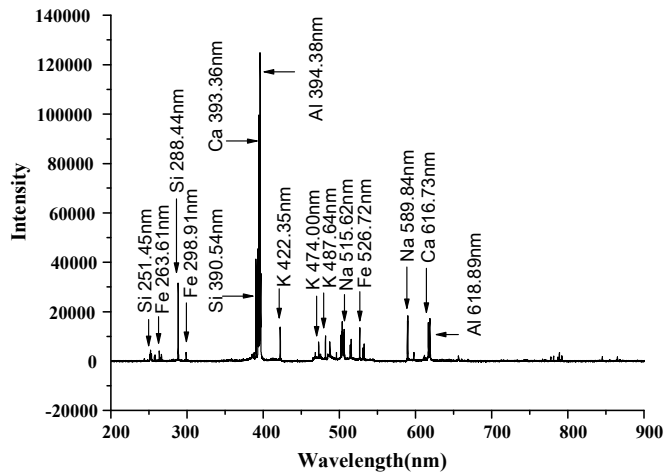


Fig.6 Emission spectra of natural contaminated sample in 200-900nm band

Fig.7 is the comparison diagram of LIBS experiment results for four types of natural contaminated insulators. Fig.8 is the comparison diagram of the intensity of some elements extracted from the spectrum. It can be seen from the figure that there is a certain difference in the strength of each element in the four types of samples with the increase of the

contamination years. And these elements all show an increase in the intensity as the contamination years increases. This change in the content of surface contamination elements with the increase of the contamination years of the sample provides an evaluation basis for the LIBS technology to evaluate the state of the insulator.

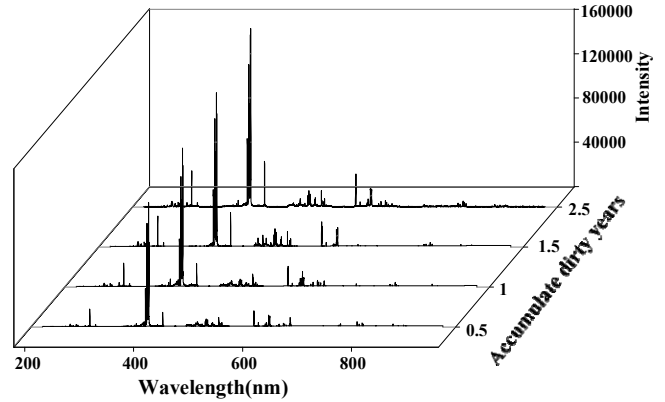


Fig.7 Emission spectra of insulators with different contamination years

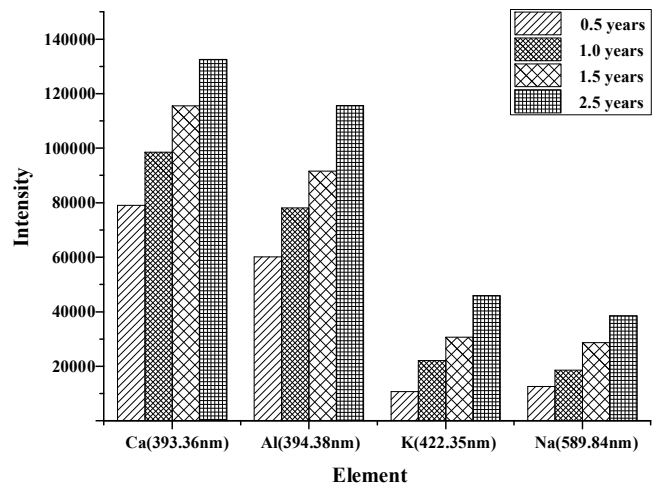


Fig.8 Comparison of partially excited state intensity of insulators with different contamination years

Due to the influence of laser energy and matrix effect on LIBS spectral intensity, there is a relatively large error in evaluating the contamination level by using the intensity difference of single dot. Because there are many kinds of contaminated elements, the reliability of using single element spectral line strength for analysis is low. Therefore, it is proposed to analyze the contamination level by using the spectral line strength of multiple elements. While, due to the overlap of the contamination information reflected by each element, the complexity of the model will be increased if the spectral intensity is extracted directly to evaluate the contamination level. Moreover, the linear relationship between the elements will lead to large errors in the model. In order to evaluate the contamination level by using the spectral line strength of elements quickly and accurately, it is necessary to reduce the dimension of the spectral line strength of many

elements, so that a few characteristic quantities can be used for analysis. In this paper, principal component analysis (PCA) algorithm was used to model and analyze.

C. Fast Classification of PCA Algorithm

The LIBS spectral intensity is proportional to the corresponding element content, so the measured spectral intensity value reflects the element content in the measured object. There are obvious differences in the element content on the surface of insulators under different contamination levels. According to this feature, the characteristic spectral lines in the contamination characteristic spectrum can be selected for rapid classification. A spectrum is usually composed of thousands of data points with many variables. Generally, there is a certain correlation between the variables, and the information they provide overlaps to a certain extent. Therefore, PCA algorithm can be used to deal with multi-variables and construct a set of new variables which are as few as possible and not related to each other. The information provided by these new variables can basically cover all the information contained in the initial variable set.

Because of the large number of spectral lines, if all the lines are selected, the workload will be greatly increased, so it needs to be screened. The principles for screening spectral lines are as follows:

- (1)The intensity of spectral lines should be high in order to reduce the interference of noise on the reading of spectral lines;
- (2)High probability of excitation to ensure that it can be fired every time;
- (3)No strong interference lines around, which can eliminate the spectral lines influence of other elements on the characteristic spectral lines.

According to the principles above, the information of spectral lines be selected is shown in TABLE II.

TABLE II

THE CHARACTERISTIC SPECTRAL LINES IN THE EXPERIMENT

Element	Excited state
Fe	526.72nm
Si	288.44nm
Ca	393.36nm
Al	394.38nm
K	422.35nm
Na	589.84nm

15 samples were collected for each contamination years. Spectral acquisition was carried out for these 60 samples, and the peak values of six characteristic spectral lines in each spectrum were extracted and a matrix of 60×6 was constructed. The matrix is processed according to the process of PCA algorithm and the cumulative variance contribution rate of each principal component was obtained. The results are shown in Table III.

TABLE III

THE CONTRIBUTION RATES OF 6 PRINCIPLE COMPONENTS

PC	Contribution rate(%)	Acumulative contribution rate(%)
PC1	82.297	82.297
PC2	16.935	99.232
PC3	0.522	99.754
PC4	0.107	99.861
PC5	0.110	99.971
PC6	0.029	100.000

From Table III, it can be seen that the cumulative contribution rate of the first two principal components reaches 96%. Therefore, the first two principle components are selected for the research. Therefore, the first two principal components were selected to study, and the principal component scores of each spectrum were calculated and displayed in a two-dimensional space composed of two principal component vectors. The results are shown in Fig.9.

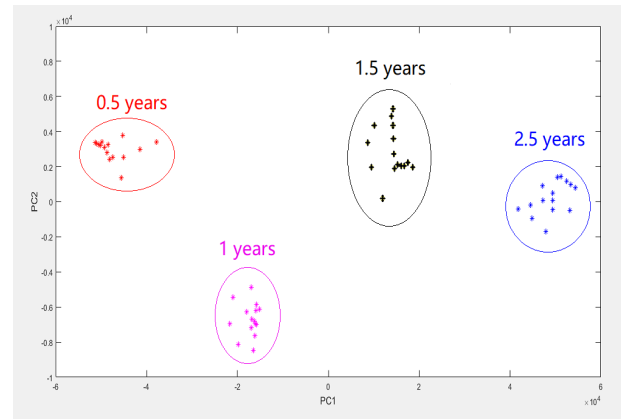


Fig.9 Classification results of PCA algorithm

From Fig.9, it can be seen that the 15 insulator samples of each contamination level have obvious convergence phenomena, which indicates that the PCA algorithm can be used to quickly judge the insulator samples of different contamination levels.

IV. CONCLUSION

This paper presents a method of insulator contamination analysis using LIBS technology. Based on LIBS technology, the artificial contaminated insulator sheets under different contamination levels and natural contaminated insulators with different contamination years were tested and analyzed. The following conclusions are drawn:

- (1)The LIBS spectrum of contaminated insulator contains the information of element composition and element content in the contamination, while the composition and content of contaminated elements of the same contamination level are similar, so their spectral information has common characteristics. Through the analysis of artificial contaminated elements, it is found that the intensity of Na element varies

significantly under different equivalent salt deposit density of insulators, while the intensity of Al element spectrum changes slightly under the same non-soluble deposit density level.

(2) There are obvious differences in the content of contaminated elements on insulator surface with different contamination years. The LIBS experiments show that the spectral intensity of contaminated elements also shows a similar discipline. With the increase of contamination years, the spectral intensity of contaminated elements increases.

(3) By extracting 6 elements of Fe (526.72 nm), Si (288.44 nm), Ca (393.36 nm), Al (394.38 nm), K (422.35 nm) and Na (589.84 nm) from natural contamination elements, and using PCA algorithm to reduce dimension, the insulators with different contamination years can be quickly classified. The results show that the LIBS technology combined with PCA algorithm can effectively evaluate the contamination level of insulators.

ACKNOWLEDGMENT

Thanks for the funding of the open fund of National Engineering Laboratory for Ultra High Voltage Engineering Technology (Kunming, Guangzhou)

REFERENCES

[1] X. Chen, P. Lu, W. Wu, et al, "A new method for the insulator pollution

grade judgement", *China Southern Power Grid Technology*, vol.3, No.2, pp.53-55, 2009.

[2] Z. Guan, "Insulators and external insulation of power transmission and transformation equipment", *Beijing: Tsinghua University Press*, pp.182-185, 2006.

[3] H. Li, G. Liu, L. Li, "Study status and prospect of natural contamination component on insulator surface", *Proceedings of the CSEE*, vol.31, No.16, pp.128-137, 2011.

[4] X. Liang, Y. Zhang, Y. Gao, "Concept and test method of effective equivalent salt deposit density for silicone rubber composit insulators", *High Voltage Engineering*, vol.39, No.12, pp.3044-3051, 2013.

[5] State Grid Corporation Q/GDW 152—2006 Power system pollution area classification and external insulation selection criteria[S], *Beijing: China Electric Power Press*, 2006.

[6] Z. Guan, C. Guo, W. Wang, et al, "Measurement of contamination distribution on the hydrophobic surface of insulators by a partial surface conductivity method", *High Voltage Technology*, vol.40, No.4, pp.957-964, 2014.

[7] L. Jin, H. Jiang, F. Yang, et al, "Pollution status detection of insulators in contact net based on UV imaging", *High Voltage Engineering*, vol.41, No.11, pp.3561-3568, 2015.

[8] C. Xie, "Study of the spectral data processing in laser induced breakdown spectroscopy analysis and its application in elemental analysis of coal", *Huazhong University of Science and Technology*, 2009.

[9] Z. Wang, "Laser induced breakdown spectroscopy technique and its application in minerals elemental analysis", *Beijing Jiaotong University*, 2007.

[10] W. Wu, X. Ma, H. Zhao, et al, "Quantitative Determination of Trace Heavy Metal Elements in Soil by Laser Induced Breakdown Spectroscopy", *Spectroscopy and Spectral Analysis*, vol.31, No.2, pp.452-455, 2011