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Leakage Current Response Mechanism of Insulator String With Ambient Humidity on Days Without Rain

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ABSTRACT The leakage current, which is influenced by the operating voltage, the surface contamination, and environmental variables, is one of the most basic online monitoring parameters for the surface contamination status of insulators. However, the impact of temperature and humidity on leakage current have not been expressed concisely nor distinguished according to sunny and rainy weather. In this paper, based on leakage current online monitoring data, the time-domain waveforms of leakage current of an insulator string in Shenzhen, China, were compared with those of the ambient temperature and humidity. Results indicate that the leakage current presents a saddle-shaped curve on days without rain, and that there is a remarkable positive correlation between leakage current and humidity as well as a negative correlation between leakage current and temperature. In a short period (several days) without rain, as long as the relative humidity keeps constant, the leakage current would vary insignificantly, whereas it may vary in a wide range at the same temperature. Moreover, the functional relation mathematical model $I = a * e^{b*RH}$ between the first harmonic component of leakage current and the relative humidity is presented, inferring that the insulator string leakage current depends mainly on the ambient relative humidity in a day without rain.

INDEX TERMS Leakage current, ambient temperature, relative humidity, insulator string, on-line monitoring, response mechanism.

I. INTRODUCTION

Contamination flashover of insulators is one of the main reasons that endanger the safe operation of power grid. During the 1990s, a total of 150 trips occurred in 220 kV line of Fujian power grid within one month from January 14 to February 15, 1996. Pollution flashover trips occurred more than 70 times in 220 kV transmission line of Putian, Quanzhou and Shishi [1]. Moreover, several inter-province flashover accidents occurred in China. For example, in 1990, due to the continuous fog, rain and snow, five 220 kV substations and seven 110 kV substations in Henan power grid partly and entirely failed, which caused a large area power outage. In 2001, heavy rain and snow with dense fog occurred several times in most of North China and Liaoning Province. Pollution flashover first occurred in Henan power grid and then developed northwards gradually, through Hebei and Beijing Tianjin Tangshan power grid until South Liaoning. In this flashover accident, 238 transmission lines ranging from 66 kV to 500 kV and 34 substations tripped 972 times [2]. Once external accidents happened, it may result in large-scale power blackout or even a breakdown of regional power network.

The basic cause of a large area contamination flashover accident is that the external insulation level is lower than requirements for contamination level. Surface contamination composed of water soluble and non-soluble or inert materials [3] attached to external insulation causes deterioration of insulation, hence it is of importance to do regular cleaning of electrical equipment to improve its insulation performance. According to the measurement of the equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD) [4], guidance can be given to external insulation and measures can be taken to adjust the creepage distance. Based on the ESDD

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and NSDD value, various standards or technical reports such as CIGRE [5], IEEE [6], IEC 60815 [7] and IEC 60507 [8] have been developed for pollution degree classification [9].

In order to estimate the contamination situation of insulators, dozens of pollution measuring points have been set up to measure the ESDD value [9], this method is widely used in China, and the power operation unit has accumulated a great deal of measurement data [10]. However, it can't provide the real-time contamination status of insulators since the measurement of ESDD is usually undertook once a year. On the other hand, it consumes too much resource to measure these date, and the data is always imprecise and insufficient because the influence of no operating voltage [11]. In other words, there are deficiencies in judging the level of contamination with the ESDD value.

Leakage current is the comprehensive reflection and final result of three essential factors of applied voltage, environmental variables and contamination, which makes it called as one of the most effective dynamic parameters to express contamination levels [12]. From the viewpoint of reflecting real-time insulator performance and minimizing risk of damage to people and property, it is urgent to develop methods for monitoring outdoor insulator performance in contaminated environments [13].

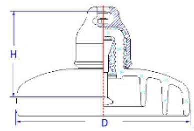
Studies have been performed using leakage current to monitor the contaminated condition of outdoor insulators [14] and predict the contamination flashovers [15]. Some scholars employ the surge counting, the current peak recording and the charge measurement as the evaluation and monitoring methods [16], [17]. Methods of wavelet transform, Fourier series and spectral analysis were used to analyze the frequency characteristics for the evaluation and monitoring [18], [19]. For example, Suda investigated the leakage current waveforms and the frequency characteristics of a string of 120-kN suspension insulators with artificial contamination tests and field tests, he found that a threshold exists in the magnitude of peak leakage current and prominent odd-order harmonic components by which the occurrence of flashover can be predicted [20]. Jahromi *et al.* [21] introduced a neural network approach to the prediction of the leakage current (LC) on silicone rubber insulators exposed to salt-fog, and a feedforward network using two hidden layers predicts the LC within 12% error was compared with other training schemes evaluated.

According to current research, leakage current of polluted insulators is affected by many factors such as ESDD, NSDD, temperature and relative humidity [22]. However, these factors are always not considered separately in outdoor experiments, whereas in laboratory experiments the temperature and humidity are relatively fixed, making it difficult to find the dynamic relationship between leakage current and temperature and humidity.

In this paper, based on leakage current on-line monitoring system, the trend and the dynamic relationship of leakage current and ambient temperature and humidity for a month are shown and compared separately.

FIGURE 1. Photo of the on-line monitoring equipment.

TABLE 1. Insulator parameter and configuration.

Main Dimension and Parameter	Configuration
Diameter (D) = 255 mm Height (H) = 146 mm Leakage Distance = 400 mm Number of Unit = 8 units Net Weight = 5.2 kg	

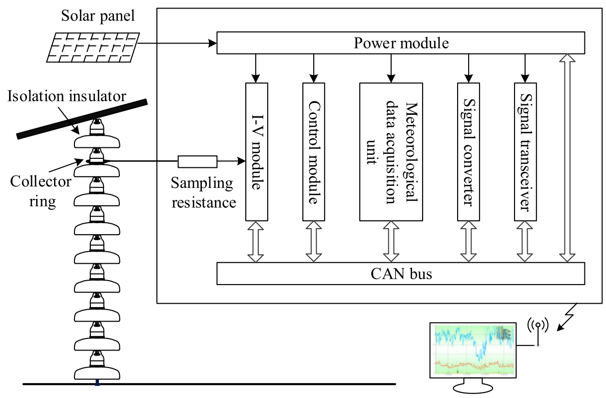


FIGURE 2. Functional diagram of leakage current on-line monitoring system.

II. LEAKAGE CURRENT ON-LINE MONITORING

The observation point of the 110 kV transmission lines under study is on the eastern area of Shenzhen, which locates in the south of Guangdong Province, China and on the East Bank of the Pearl River Delta. It has a subtropical marine climate characterized by hot and rainy summers and other relatively dry seasons. Rainfall is plentiful and the rainy season normally starts in April and lasts until late September.

The on-line monitoring equipment was set up on the tower as shown in Fig. 1. The test sample is an 8-unit glass insulator string, with the schematic configuration, dimensions and parameters listed in Table 1.

Fig. 2 shows the functional diagram of leakage current on-line monitoring system, where an isolation insulator is added between the tower arm and the first insulator to minimize interference. The leakage current was obtained through the sampling resistance and then into earth, where the sampling resistance is parallel connected to an added isolation insulator.

The I-V module converts leakage current signals into voltage signals and then it is sent to the signal converter. The maximum sample rate of leakage current is 250kS/s. The meteorological data acquisition unit consists of four parts: thermometer and hygrometer, atmospheric pressure gauge, anemometer and raingauge. The measurement precision of rainfall, temperature, relative humidity and leakage current is 0.1mm, 0.1°C, 1%, and 0.01 mA.

The control module controls the meteorological data acquisition unit for data acquisition such as ambient temperature and humidity and then the signal converter is responsible for data validity identification and data integration. The signal transceiver transmits data processed by the signal converter to host monitor through the network. All the functional units are connected through the CAN bus.

At the specified time, control module sends instructions to meteorological data acquisition unit for getting per minute data of ambient temperature and humidity and to I-V module for sending per minute data of the leakage current to the signal converter. After that, the signal converter identifies the validity of the data, adds time stamps, packages the data and then sends the packaged data to the signal transceiver through the CAN bus and enters the suspended state. When the signal transceiver receives the signals, it connects with the host monitor and sends the data through the network.

The solar panel provides power for the monitoring device, the power output terminal of the power module is connected with each module to supply power, and the operation status of each module is obtained by CAN bus. Once any functional unit runs abnormally, the power supply module would restart all functional units including itself.

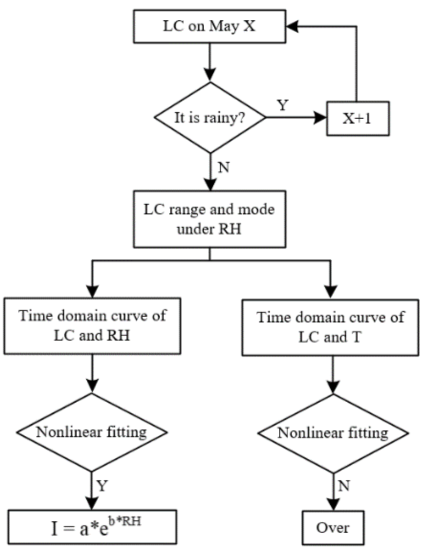


FIGURE 3. Flow chart of the entire process.

The flow chart listed in Fig.3 is for the sake of understanding the studying process of the relationship between the leakage current (LC) and relative humidity (RH) and temperature (T) in this paper.

III. LEAKAGE CURRENT ANALYSIS AND RESULTS

A. LEAKAGE CURRENT ON DAYS WITHOUT RAIN

Considering that harmonic components of insulator leakage current are always generated by some uncertainties such as corona etc., the first harmonic component of leakage current was used to study the relationship between the leakage current of insulator string and the ambient temperature and humidity. In order to figure out the influence of environmental variables on leakage current on days without rain, the domain waveforms of leakage current, ambient temperature and humidity on May 2016 are shown in Fig. 4. From the figures what is clearly revealed that the leakage current changed smoothly and regularly with time, except when the rainfall occurred, and the leakage current fluctuated up and down in an almost certain range on days without rain. The fluctuations of temperature and humidity were also very regular and their diurnal variation showed a single-peak curve. When the temperature reached its peak, the trough of the relative humidity appeared at around the same time.

The days without rain on May are extracted, and the range of the first harmonic component of leakage current are counted as showed in Table 2, where mode in Table 2 is the value that appears most frequently in the numbers of range. In order to reduce the impact of rainfall on statistical data, although some days like May 7 were not rainy, they are excluded because it was raining within 12 hours before or after the day. Therefore, there are a total of 12 days on May being counted.

Since the relative humidity is divided every five percent, most of the difference between the minimum and maximum value of the leakage current in each table cell is less than 0.05 mA, which means if the relative humidity is confirmed, the leakage current varies little at any time in a day.

Besides, when the relative humidity is under 80%, the range and mode of leakage current in each row in Table 2 vary within 0.13 mA and 0.09 mA, while within 0.19 mA and 0.12 mA when the relative humidity is more than 80%. It presents that the leakage current in the row varies less when the relative humidity is low. As for a short period without rain such as the days from May 11 to May 14, the mode of leakage current in each row only change a bit, which can be deduced that when the insulator surface contamination remains unchanged, the leakage current would be almost the same under the same relative humidity.

In each column, most of the mode of the leakage current increases less than 0.06 mA with every 5% increase of relative humidity, exceptions exist that on May 12 the leakage current increased 0.09 mA when the relative humidity increased from 80% – 84% to 85% – 89%. Therefore, considering that when the relative humidity is under 80%, the mode of the leakage current increases within 0.03 mA in each column except May 24, the regularity can be found that the leakage current increases faster when the relative humidity is at a high level.

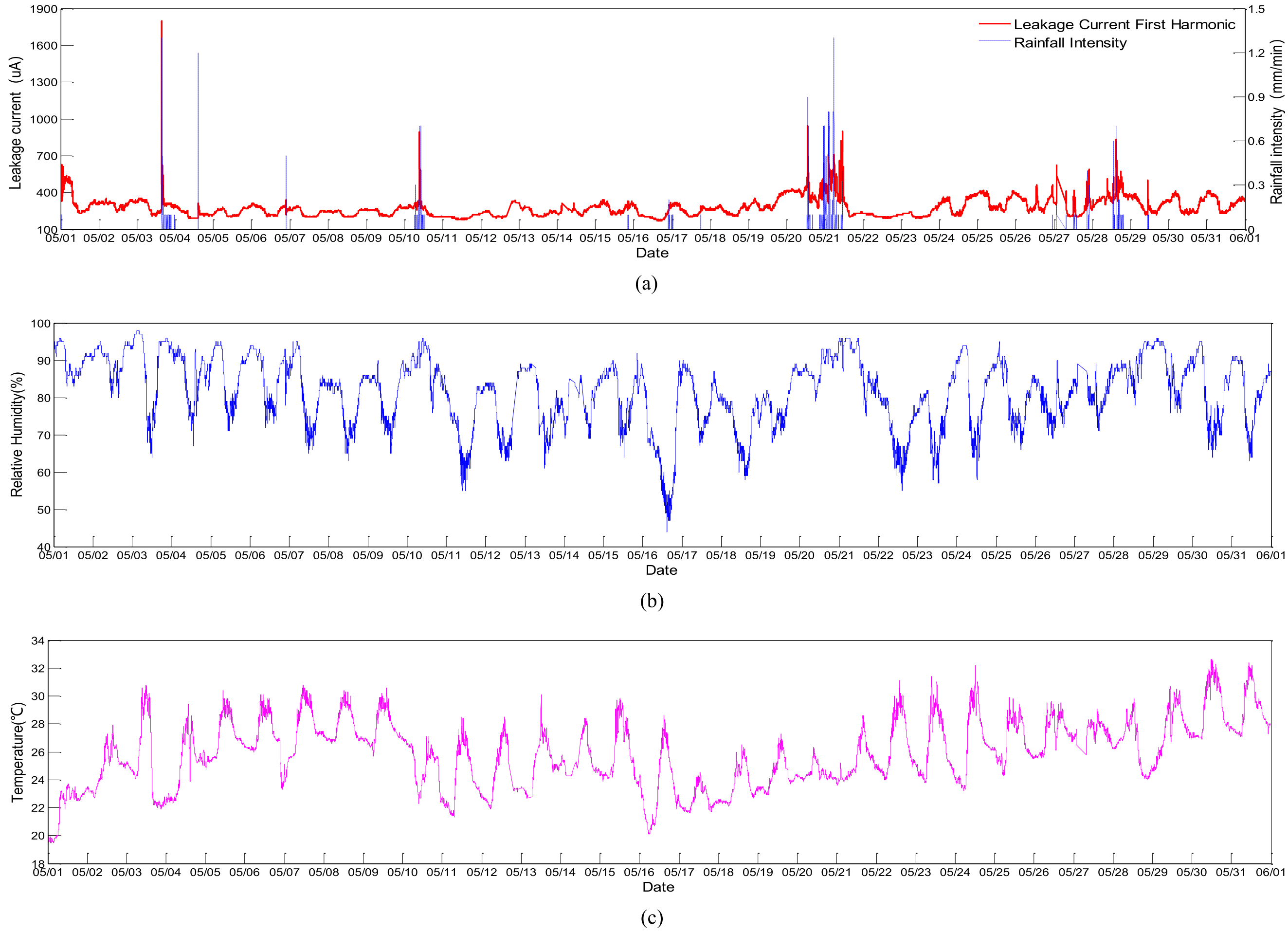


FIGURE 4. Data recorded by leakage current on-line monitoring system. (a) Leakage current and rainfall intensity on May 2016. (b) Relative humidity on May 2016. (c) Ambient temperature on May 2016.

B. RELATIONSHIP BETWEEN LEAKAGE CURRENT AND AMBIENT HUMIDITY

In order to find out the further relationship between leakage current and ambient humidity, six days without rain are picked out from Table 2, and their time domain curves of the leakage current and relative humidity are compared in Fig. 5. It is obvious that the leakage current presents remarkable positive correlation to the relative humidity. The leakage current remains at a relatively high level in the morning and at night, and falls to the bottom around noon, showing a saddle-shaped curve, just like the relative humidity does.

Because the leakage current synchronizes with the variations of the relative humidity, and increases faster with the increase of the relative humidity when the relative humidity is at a high level, the curves of nonlinear fitting of the leakage current and relative humidity on the six days without rain are drawn in Fig. 6. And the fitting curves fit the data recorded by the on-line monitoring equipment very well. Furthermore, the R^2 in Fig. 6 called coefficient of determination of every chosen day is greater than 0.8, which means the mathematical equation $I = a * e^{b*RH}$ can express the correspondence between the first harmonic component of leakage current and relative humidity on the day without rain. Because of the influence of natural contamination deposition on insulator string and the rainfall flushing contributing to impact to the leakage current, the coefficients of a and b are not the same on the six chosen days. However, the leakage current fluctuations are maintained within the small range under the same relative humidity especially in a short period without rain.

Taking all these phenomena above and the function model $I = a^{*}e^{b*RH}$ into account, conclusions can be draw that the leakage current of insulator string is significantly dominated by ambient relative humidity in a day.

C. RELATIONSHIP BETWEEN LEAKAGE CURRENT AND AMBIENT TEMPERATURE

The temperature and relative humidity in Fig. 4 shows a negative correlation and the relative humidity has already been proved to have mathematical function relation to the leakage current first harmonic. In order to find out the relationship between the leakage current and ambient temperature on days

TABLE 2. Range of leakage current on days without rain.

RH (%)	LC on May 2 (mA)		LC on May 8 (mA)		LC on May 11 (mA)		LC on May 12 (mA)		LC on May 13 (mA)		LC on May 14 (mA)	
	Range	Mode	Range	Mode	Range	Mode	Range	Mode	Range	Mode	Range	Mode
55 – 59					0.18	0.18						
60 – 64					0.18 – 0.19	0.18	0.19 – 0.2	0.2	0.2 – 0.21	0.2		
65 – 69			0.21 – 0.23	0.22	0.18 – 0.19	0.19	0.19 – 0.21	0.2	0.2 – 0.22	0.2	0.21	0.21
70 – 74			0.21 – 0.23	0.23	0.19 – 0.2	0.19	0.2 – 0.22	0.21	0.2 – 0.23	0.21	0.21 – 0.23	0.22
75 – 79			0.23 – 0.25	0.23	0.19 – 0.21	0.2	0.21 – 0.23	0.22	0.21 – 0.25	0.24	0.22 – 0.25	0.23
80 – 84	0.25 – 0.27	0.25	0.25 – 0.28	0.26	0.2 – 0.23	0.22	0.23 – 0.25	0.24	0.23 – 0.27	0.24	0.24 – 0.29	0.28
85 – 89	0.26 – 0.31	0.28	0.26 – 0.29	0.28			0.31 – 0.34	0.33	0.26 – 0.32	0.27	0.26 – 0.3	0.29
90 – 95	0.3 – 0.34	0.32										

RH (%)	LC on May 19 (mA)		LC on May 23 (mA)		LC on May 24 (mA)		LC on May 25 (mA)		LC on May 30 (mA)		LC on May 31 (mA)	
	Range	Mode	Range	Mode	Range	Mode	Range	Mode	Range	Mode	Range	Mode
55 – 59			0.19 – 0.2	0.19	0.21 – 0.22	0.21						
60 – 64			0.19 – 0.2	0.2	0.21 – 0.23	0.22					0.23 – 0.25	0.23
65 – 69	0.25	0.25	0.19 – 0.21	0.2	0.21 – 0.24	0.22	0.25 – 0.27	0.25	0.22 – 0.25	0.23	0.23 – 0.25	0.23
70 – 74	0.25 – 0.28	0.26	0.2 – 0.22	0.2	0.22 – 0.26	0.23	0.25 – 0.29	0.28	0.23 – 0.26	0.24	0.23 – 0.26	0.24
75 – 79	0.27 – 0.32	0.29	0.21 – 0.23	0.22	0.25 – 0.3	0.29	0.26 – 0.31	0.28	0.24 – 0.28	0.25	0.24 – 0.29	0.27
80 – 84	0.29 – 0.35	0.33	0.23 – 0.27	0.23	0.28 – 0.31	0.3	0.33 – 0.39	0.36	0.25 – 0.34	0.34	0.28 – 0.34	0.3
85 – 89	0.36 – 0.41	0.39	0.27 – 0.3	0.27	0.3 – 0.35	0.34	0.36 – 0.41	0.39	0.31 – 0.38	0.34	0.32 – 0.38	0.34
90 – 95			0.3 – 0.32	0.3	0.35 – 0.39	0.37	0.38 – 0.41	0.4	0.33 – 0.4	0.38	0.36 – 0.41	0.4

Notes: LC: the first harmonic component of leakage current; RH: relative humidity; The relative humidity on days without rain is divided every 5 percent, and the range of the leakage current are counted in each section.

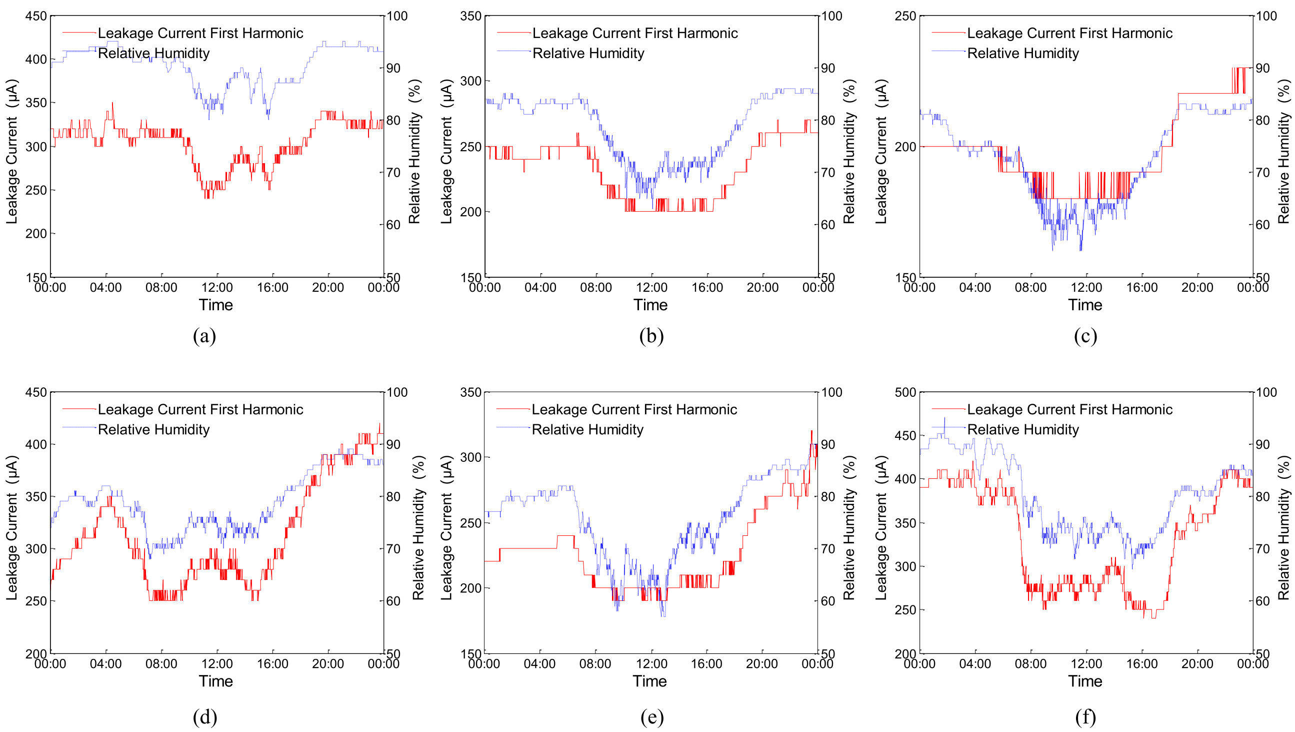


FIGURE 5. Time domain curves of the first harmonic component of leakage current versus relative humidity on days without rain. (a) May 2. (b) May 8. (c) May 11. (d) May 19. (e) May 23. (f) May 25.

without rain, the same six days' time domain curves of the first harmonic of leakage current and temperature are compared in Fig. 7. Obviously, the temperature has a remarkable negative correlation with the leakage current first harmonic component, contrary to the relative humidity. Once again, the curves of nonlinear fitting of the leakage current and temperature on the six days are drawn in Fig. 8 and the nonlinear fitting of temperature has as good a result on May 8 and May 25 as the one of relative humidity does. However, some of the nonlinear fitting curves of the leakage current first harmonic component and temperature in Fig. 8 don't fit the practical data well on several days such as May 2, May 11 and May 19, and the coefficient determination R^2 on these three days is much less than 1. Moreover, when the temperature

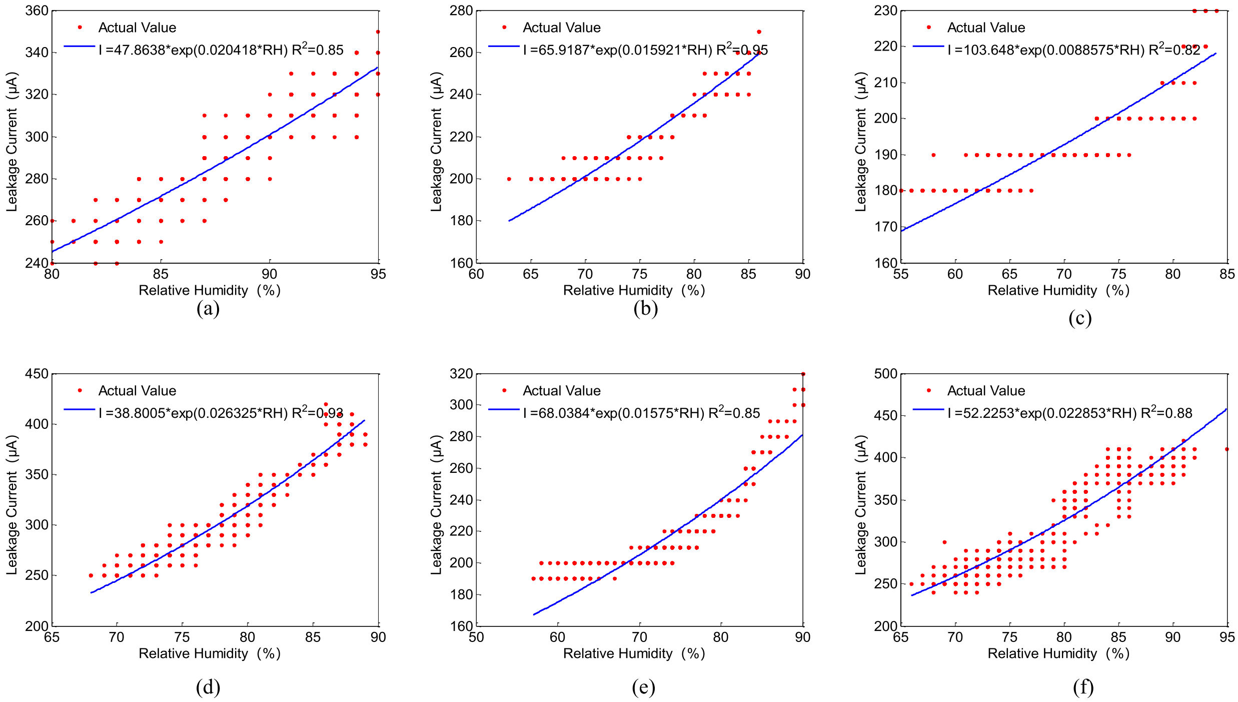


FIGURE 6. Nonlinear fitting curve of the first harmonic component of leakage current versus relative humidity on days without rain. (a) May 2. (b) May 8. (c) May 11. (d) May 19. (e) May 23. (f) May 25.

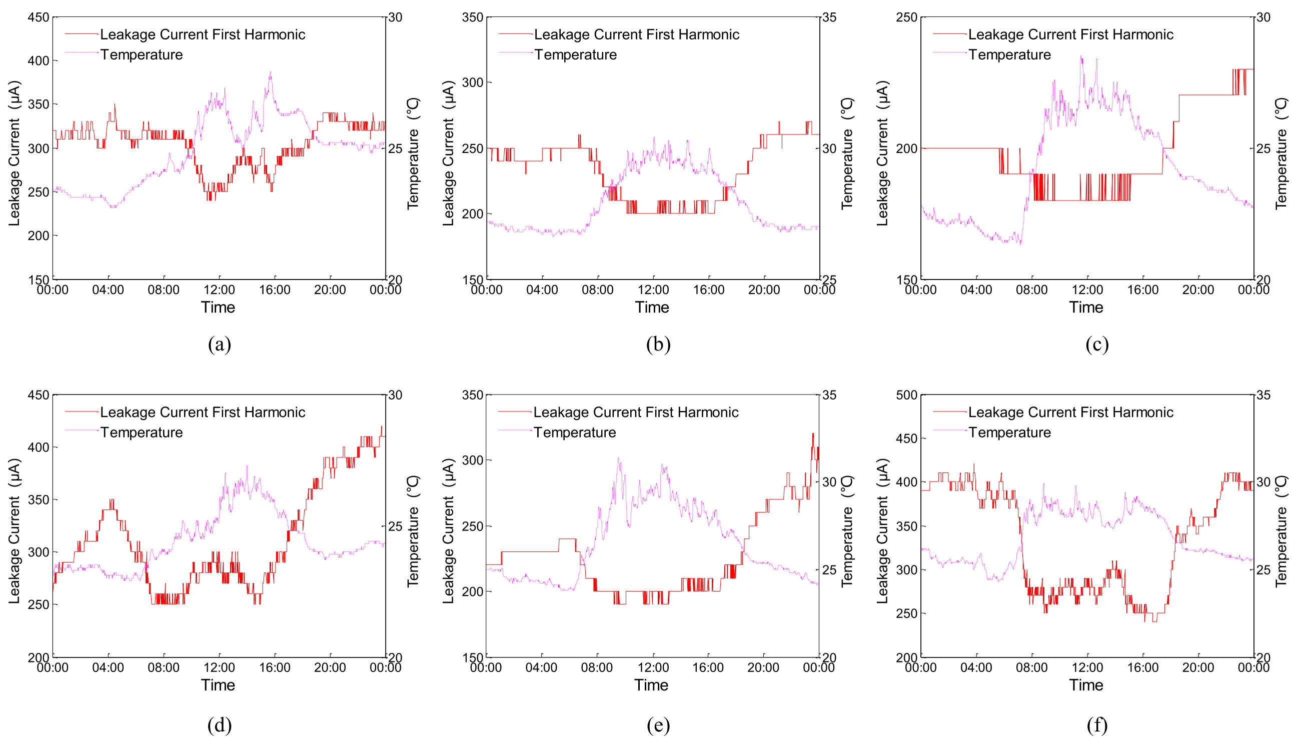


FIGURE 7. Time domain curves of leakage current first harmonic versus temperature on days without rain. (a) May 2. (b) May 8. (c) May 11. (d) May 19. (e) May 23. (f) May 25.

is certain, the leakage current first harmonic varies over a wide range, even reaches the maximum and minimum at the same temperature on May 19.

Although there is a negative correlation between the trend of leakage current and temperature on days without rain, no explicit corresponding relationship exists between leakage

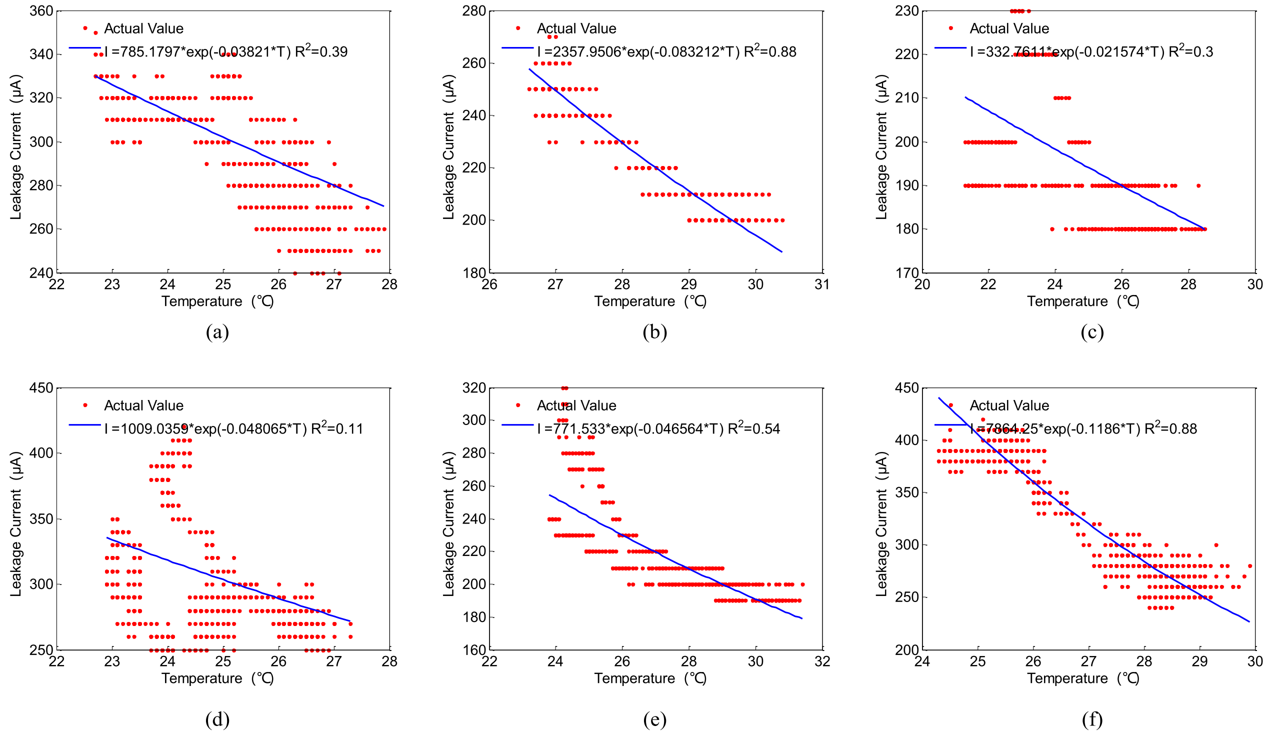


FIGURE 8. **Nonlinear fitting curve of leakage current first harmonic versus temperature on days without rain. (a) May 2. (b) May 8. (c) May 11. (d) May 19. (e) May 23. (f) May 25.**

current and temperature. When the temperature is certain, the leakage current may vary at a wide range.

IV. CONCLUSIONS

Based on leakage current on-line monitoring system on transmission line, the leakage current trend of 110 kV insulator string on days without rain and the relationship between leakage current and ambient temperature and humidity were investigated in this paper. The main results are as follows.

1) The leakage current on days without rain shows a saddle-shaped curve, and it remains at a relatively high level in the morning and at night, and falls to the bottom around noon.

2) The leakage current presents remarkable positive correlation to relative humidity, and negative correlation to temperature to a certain extent on days without rain.

3) The leakage current can be affected by ambient temperature and humidity, but it depends mainly on relative humidity in the day.

4) In a short period without rainfall, as long as the relative humidity keeps constant, the leakage current varies insignificantly.

5) The leakage current increases faster with the increase of the relative humidity when the relative humidity is at a high level.

6) The leakage current response model of insulator string with ambient humidity on days without rain can be expressed by the equation $I = a * e^{b*RH}$.

The main purpose of this paper is to find out the main influence factors of leakage current of insulator string under operating voltage. The leakage current response mechanism of insulator string on days has been presented, and the influence of environmental variables on leakage current has been quantified. By making clear the change of the leakage current on days and finding the cause of the change, the contamination status of insulator string can be assessed according to the leakage current.

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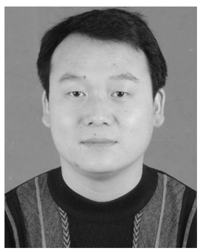

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