Research on the detection of arc fault in series connection of landscape power supply

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Abstract—Aiming at the series fault arc phenomenon in landscape lighting and the hidden dangers of electrical fires, in this paper, a landscape power supply series fault arc model is constructed and its model is simulated. The simulation results show that when a fault occurs, the arc current becomes smaller (almost zero) due to the increase in the impedance of the lighting circuit; this phenomenon is called the “current zero off” phenomenon of the fault arc current. The current zero off phenomenon of the fault arc current is the main fault feature in the landscape lighting circuit. In this paper, the wavelet algorithm is used to detect the fault current waveform. According to the fault characteristics, by judging whether the modulus maximum value of the wavelet coefficient has periodic characteristics with an interval of 100±15 sampling points, it is analyzed whether a series-type arc fault occurs. The built physical model verifies the feasibility and correctness of the arc detection algorithm. The research results of this paper have certain reference value for the detection and application of fault arc.

1. Introduction
People's yearning and pursuit of a better life has promoted the vigorous development of urban landscape lighting. Urban landscape lighting has highlighted the rapid development and characteristics of the city, thereby enhancing people's recognition and confidence in the country and society. In urban landscape lighting, visual and aesthetic requirements require the use of high-power power supplies to drive various street lights, LED lights and landscape lights. People can not ignore the safety problem of landscape power supply (electrical fire) while enjoying a good life. The safety issue of landscape power supply has become one of the hotspots in the research of lighting engineering.

A large amount of research data shows that arc faults in low-voltage distribution lines are the most important cause of electrical fires. An arc occurs when a line or equipment fails; its temperature will increase sharply, and an arc current of 2-10A can produce a local high temperature of 2000-4000°C; under the condition of a 220V AC power supply voltage, an arc will be drawn when the current exceeds 0.5A[1]. If the fault arc in the line is not detected and eliminated in time, the temperature of the
fault point will gradually increase. When the temperature reaches a certain level, it can ignite the surrounding combustibles, and may involve other lines, causing electrical fires; in severe cases, large-scale power outages and explosions in the distribution system may occur, causing unpredictable economic and social losses[2].

According to the location where the arc occurs, arc faults can generally be divided into series fault arcs, parallel fault arcs and ground fault arcs, with ground fault arcs classified as parallel fault arcs[1]. Parallel fault arc is mainly caused by overload, short circuit and other reasons; the effective value of current is relatively large, generally 75-500A. Traditional protection devices such as circuit breakers, fuses and residual current-operated protectors in low-voltage distribution lines can provide effective protection against parallel fault arcs. The series fault arc is equivalent to a dynamically changing resistance; the dynamic resistance is connected in series with the load of the normal operation of the line, so that the loop current becomes smaller when a fault occurs; the current change range is 5-30A, or even lower, and its small fault current is not easy to cause the relay protection device in the low-voltage distribution line to operate[3].

The distance of the landscape lighting power distribution circuit is relatively long, so no matter whether the grounding mode is TN system or TT system, when a series fault arc occurs, the circuit impedance increases and the fault current is small; the fault current is not enough to cause the circuit breaker overcurrent protection action and the fuse and residual current action protector action, this phenomenon is called the "current zero off" phenomenon[4]. In order to solve the harm of series arc fault, it is necessary to effectively detect the series arc fault generated by the landscape lighting power distribution circuit. Based on this, this paper constructs a landscape power supply series arc fault model, and conducts simulation and physical verification of the model.

2. Construction of a Series Fault Arc Model for Landscape Power Supply

The series arc fault is one of the main causes of electrical fires in the landscape power supply lighting system. To study the landscape power supply series fault arc, it is necessary to effectively detect the arc signal, and to detect the arc signal, it is necessary to build a fault arc model. The landscape power supply series fault arc detection structure is shown in Figure 1.

Fig.1 Structure diagram for landscape power supply series fault arc detection

The structure diagram for landscape power supply series fault arc detection is composed of landscape power supply, LED lamp load and fault arc detection.

For landscape power supplies, a slight change in the forward voltage of the LED lamp will cause a drastic change in its forward current, resulting in a significant change in its brightness. In order to keep the brightness of the LED lamp stable, in this study, a constant current driving method is adopted as the design scheme for the landscape power supply.

Arc fault refers to the change of the air gap between the two electrodes from insulation to a medium, thereby forming a continuous discharge phenomenon, accompanied by strong heating, light emission, etc., which is a very complicated electromagnetic response process[5]. After the fault arc occurs, the circuit can not be opened quickly, and the electrical equipment will be damaged; in severe cases, it may cause wiring and equipment failures, and even electrical fires and explosions, which may bring life danger to people around. In order to accurately detect the generation time and fault characteristics of the series fault arc, it is necessary to establish a fault arc model and analyze the
characteristics of the fault arc. The following is a brief analysis of the construction method for the Schwarz arc model.

As a modified model of the Mayr arc model, the Schwarz arc model sets the time constant and the dissipated power as the power function of the arc conductance. The power function is selected to simulate the arc fault change, which is more in line with the actual arcing process. According to the assumptions of the Schwarz arc model, we obtain the formula

$$\tau_M = \tau_s \times g^\alpha$$
$$P_{loss} = P_s \times g^\beta$$

(1)

In the formula, $P_s$ is the dissipation power coefficient, $\tau_s$ is the time constant coefficient, $\alpha$ is the exponential component of the time constant $\tau_M$, and $\beta$ is the exponential component of the dissipation power $P_{loss}$.

Substituting the assumptions of the Schwarz arc model into the principle of conservation of energy and the general mathematical model of the arc, the arc differential equation of the Schwarz arc model can be obtained.

$$\frac{1}{g} \times \frac{dg}{dt} = \frac{1}{\tau_M} \left( \frac{gu^2}{P_{loss}} - 1 \right)$$

(2)

In the formula, $g$ is the arc conductance.

According to formulas (1) and (2), a Schwarz arc simulation model can be constructed, as shown in Figure 2.

Fig.2 Schwarz arc simulation model

In Figure 2, the Ideal switch is an ideal switch. When Step is low, the ideal switch is turned on, the differential equation encapsulated in the arc model is short-circuited, and the analog circuit operates normally. When Step changes from low level to high level, the ideal switch is turned off, and the differential equation package is turned on for differential calculation, which simulates a series-type fault arc. The ODE subsystem is a packaged series-type arc fault mathematical model.

The simulation model of the landscape power supply series arc fault is shown in Fig.3.
The series arc fault model of landscape power supply includes Schwarz arc model, constant current and constant voltage power supply model, nonlinear load (LED lamp) equivalent resistance, etc.\cite{9}

The landscape power supply series fault arc model reflects the physical relationship between landscape power supply, LED lamp load and fault arc, and using this model simulation we can understand the influence of the fault arc on the landscape power supply and load.

3. Simulation of series fault arc in landscape power supply

According to the simulation model of the series arc fault of the landscape power supply in Figure 3, the following conditions and parameters are set.

(1) Set the fault occurrence time step to 0.01s when a high pulse is issued, and the switch is turned on at the same time, and the fault arc model is connected to the circuit;

(2) In the mathematical model of arc, set $\alpha$ to be -0.3 and $\beta$ to 0.5; in the landscape power supply series fault arc model, set the transformer capacity to 500VA; the current sampling resistor is 0.0032Ω; the output filter capacitor is 4700μF; the full bridge filter capacitor is 11μF.

According to the conditions and parameters set above, the simulation results are shown in Figures 4 and 5.

Figure 4 shows the current waveform of the landscape power supply when the arc occurs, and Figure 5 reflects the voltage waveform of the landscape power supply when the arc occurs.

When a fault arc occurs, at the zero crossing point of the arc current, the impedance between the fault arc air gap will become very large; in the transfer period of the first half cycle and the second half cycle of the arc current, the arc current is equal to the ratio of the voltage at both ends of the arc to the arc impedance. As the impedance becomes larger, the value of the arc current becomes very small, almost zero, and lasts for a short period of time; during this period of time, the phenomenon of this current is called the “current zero off” phenomenon of the arc current\cite{10}.

![Fig.4 Landscape power supply current waveform when arc fault occurs](image-url)
It can be seen from Figures 4 and 5 that the current “current zero off” phenomenon is more obvious, that the arc current has a rapid increase and a rapid decrease, and that the arc voltage has two spikes in half a cycle.

The voltage waveforms on both sides of the non-linear load (LED lights) obtained by simulation when the arc fault occurs are shown in Figure 6.

It can be seen from Fig.6 that the voltage on both sides of the non-linear load has a sudden change at 0.01s after the occurrence of the fault arc.

At 0.04s the voltage reaches its maximum value, and at 0.15s the voltage drops to 0V. This shows that the fault arc occurs in a short time, that the voltage starts to change suddenly and reaches the maximum value, and that the fault arc will quickly cause an electrical fire.

During normal operation, the current waveform between the mains and the landscape power supply is shown in Figure 7. When the arc fault occurs between the mains and the landscape power, the current waveform is shown in Figure 8.
Fig. 7 Current waveform between mains and landscape power

Fig. 8 Current waveform between mains and landscape power when arc fault occurs

The fault arc model is set to connect to the circuit at 0.01s. It can be seen that when a fault arc occurs, the current waveform has a current zero off phenomenon.

4. Fault arc detection algorithm

From the arc fault simulation, it is known that when a fault arc occurs, the current in the line will have a very short flat shoulder at the zero-crossing point, that is, the phenomenon of “current zero off”. The conversion of the “current zero off” phenomenon into a function is of singularity. The wavelet analysis algorithm can be used to perform the time-frequency analysis to extract the wavelet coefficients, analyze the singularity of the wavelet coefficients, and extract the characteristics of the fault signal. Because these singularities generally appear in the form of step signals or pulse signals, the interference signal in the collected current signal can be regarded as a pulse signal, and the sudden change signal can be regarded as a step signal [11-13]. In the single chip microcomputer, the power frequency cycle is set to 0.02s, the sampling frequency is set to 10kHz, and the time interval of each sampling point is set to 0.125ms. Therefore, 160 points will be collected in a power frequency cycle of the single chip microcomputer. According to the time interval of arc extinction and reburning, it can be calculated that a singular point will appear after many sampling points, so as to obtain the judgment basis.
When judging the singularity of a signal, it can be judged by the zero point or the mode extreme point, but the zero point is easily affected by high-frequency noise. The antisymmetric $\psi^2(t)$ is used as the wavelet function; this function is called orthogonal quadratic spline wavelet in mathematics, and it can fully satisfy the detection of the singularity characteristics of the fault arc current information in this paper[14].

Let $g_1(\omega)$ and $g_2(\omega)$ high-pass filters and $h_1(\omega)$ and $h_2(\omega)$ be low-pass filters, as well as finite energy scaling functions and wavelets $\Phi, \Phi^\prime, \psi$ and $\psi^\prime$. The wavelet satisfying the formula (3) is called an orthogonal dyadic wavelet.

$$
\begin{align*}
\varphi_\omega (\omega) &= \frac{1}{\sqrt{2}} h_1(\omega) \varphi \left( \frac{\omega}{2} \right) \\
\psi_\omega (\omega) &= \frac{1}{\sqrt{2}} g_1(\omega) \varphi \left( \frac{\omega}{2} \right) \\
|h_1(\omega)|^2 + |g_1(\omega)|^2 &= 2
\end{align*}
$$

The orthogonal quadratic spline wavelet is used to construct the wavelet function, and the dyadic wavelet transform is performed on the current signal collected by AD to obtain the wavelet coefficients. Then the modulus maximum value of wavelet analysis is calculated, and the periodicity of the modulus maximum value is analyzed. If the modulus maximum occurs periodically, it will be considered that a fault arc has occurred at this point.

According to the analysis of mathematical methods, the maximum value of the function modulus can be found.

1. Solve the first derivative of the function $f(x)$, and solve the value of $x$ in $f'(x)=0$. The value of $x$ is the extreme point of $f(x)$, and the solution is set to $X_0$ here.
2. Solve the second derivative of the function $f(x)$, and convert the solution $x$ in step (1). Substitute the second derivative $f''(x)$ of $f(x)$. If $f''(x)$ is greater than 0, this point is the minimum point; if $f''(x)$ is less than 0, this point is the maximum point.

Dyadic wavelet is between continuous wavelet and discrete wavelet, it just discretizes the scale parameter, but in the time domain the amount of translation still changes continuously.

Let the scale parameter $a=2^j$ and $j \in \mathbb{Z}$, with the parameter $b$ being still a continuous value, there is a dyadic wavelet.

$$
\psi_{2^j, b}(t) = 2^{-1/2} \psi [2^{-j}(t - b)]
$$

The corresponding dyadic wavelet transform is

$$
BWT_{f,n}(2^j, b) = 2^{-j/2} \int_{-\infty}^{\infty} f(t) \psi [2^{-j}(t - k)] \, dt
$$

When the singular point of the original signal suddenly changes upward, the maximum value of the wavelet coefficient is negative; when the singular point changes downward, the maximum value of the wavelet coefficient is positive. When the arc is stable, these modulus maxima appear periodically, and the range of the period is generally 100 ± 15 sampling points.

By judging whether the modulus maximum value of the wavelet coefficient has periodic characteristics with an interval of 100 ± 15 sampling points, it can be considered that a fault arc has occurred in the power supply line of the landscape power supply; if the continuous time exceeds 5 power frequency cycles, the fault arc is likely to cause an electrical fire.

5. Landscape power supply series fault arc detection verification

In order to verify the feasibility and correctness of the landscape power supply series fault arc detection, we constructed a fault arc test device, with the structure of which shown in Figure 9.

The device shown in Figure 9 includes a stationary carbon graphite electrode with a diameter of 6.4 mm and a movable copper electrode. The stationary electrode is connected to 220v alternating current, and the moving electrode can be connected to a load.

First, the two electrodes are put in a state of complete contact, that is, the line is completely closed. Then, the active electrode is slowly moved so that it is slowly separated from the stationary electrode. When the gap between the two poles reaches a certain distance, the arc occurs. After the arc occurs,
the electrode is immediately stopped moving to ensure that the arc continues to occur. At this time, we can observe the current characteristics when a fault arc occurs on the power supply line after the load is connected\cite{15}.

![Fig.9 Structure diagram for fault arc test device](image)

The current waveform at fault arc is shown in Figure 10.

![Fig.10 Waveform of fault arc current](image)

In Figure 10, the current waveform has an obvious “current zero off” phenomenon, with the arc fault detector used to verify whether the proposed algorithm can accurately determine the occurrence of the fault arc.

The hardware structure diagram for the fault arc detector is shown in Figure 11. The hardware design of the electrical fire monitoring detector is mainly divided into current transformer, signal conditioning circuit, AD acquisition circuit, main chip and its peripheral circuit, sound and light alarm circuit. The fault arc detector is shown in Figure 12.

![Fig.11 Block diagram for the hardware structure of the arc fault detector](image)
A current transformer with an accuracy ratio of 1000:1 is installed in the landscape power supply line. The current transformer can detect and transform the current signals into voltage signals. Then voltage signals are conditioned, rectified, amplified, and sent into the ADC converter of master chip. After analog-to-digital conversion, the analog voltage signals are changed into digital signals. The meaning of signal conditioning is to amplify, filter, and follow the signal. Due to the fact that detected current signals are too weak and unstable, port resources of ADC converter in master chip are not fully utilized and the error in the detection process is easy to become larger. Therefore, after appropriate amplification, filtration, and following operations, the signals are available and recognizable to the chip. Afterwards, the digital signals are sent to the DSP for data processing. The microprocessor carries out data processing by the wavelet analysis, modulus maximum and other algorithms. After this step, the microprocessor decides whether to give a sound-light alarming after pre-judging the strength of signal singularity. Besides, the DSP will send the data to the CAN bus through the CAN transceiver and then transmit them to the monitoring center for remote monitoring.

6. Conclusion
People cannot ignore the safety of landscape power supply while enjoying the beautiful environment of nature. Aiming at the series fault arc phenomenon in the landscape lighting circuit and the hidden dangers of electrical fires, we have simulated the landscape power supply series fault arc model, detected the fault current waveform, and verified the physical prototype, showing the feasibility and correctness of the research results.

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