Simulation of a single-phase arc grounding fault on a 220-kV cable transmission system

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Abstract. Cable tunnel fires are mainly caused by single-phase arc grounding faults. The massive energy generated by arc can threaten the safety of the densely laid cable tunnels. In this study, a digital arc fault model with a 220-kV cable transmission system was established on Power Systems Computer Aided Design (PSCAD). The arc model was improved because the parameters were acquired from the experimental results. The arc fault can be divided into two stages: a primary arc at the initiation of the fault and a secondary arc after the tripping of the circuit breakers. The primary arc contains few nonlinear components because of the large arc currents. The secondary arc voltages exhibit nonlinear characteristics because of arc elongation. The secondary arc power continues to increase, however, its amplitude is considerably smaller than the primary arc. The lifetime of the primary arc is dependent on the action of the relaying protection system. Further, some limits based on the energy balance theory were introduced to obtain the extinction time of the secondary arc. In addition, the total energy generated by the arc fault in the 220-kV cable transmission system will eventually become 4891 kJ. This digital arc fault model will significantly contribute to future research with respect to the mechanism of cable tunnel fires.

1. Introduction
With the rapid development of urbanization, fire accidents in cable tunnels are frequently observed with serious consequences. On June 18, 2016, the cable tunnel fire in the Weiqu substation in Shaanxi Province resulted in fires in the 110-kV Weiqu substation and 330-kV Nanjiao substation. The total amount of loss because of this accident was 243,000 kW. Therefore, it is vital to study power cable tunnels to ensure the safety of the power systems.

In China, cables are usually laid densely in tunnels to save space. The heat energy generated by the failure of any one cable can possibly ignite the cable tunnel. Single-phase grounding is the most common fault in the power transmission system. According to statistics, arc grounding faults constitute more than 80% of the single-phase grounding faults [1]. The arc grounding faults do not easily disappear with the increasing power transmission distance and transmission capacity. During the repeated re-ignition process, the arc often exhibits a rapid increase in temperature, lighting and pressure. The center temperature of the arc column can likely reach 5000 K–15000 K [2], causing hidden fire dangers in tunnels.

The black box arc model is one of the best choices to study the transient process of the single-phase arc grounding faults. The objective of arc models is to use the voltage and current traces obtained from...
tests combined with a given mathematical differential equation to deduce a mathematical model\([3]\), which can be used to predict the transient process of the arc grounding faults under any conditions. The arc fault can be divided into two stages: the primary arc with high currents when the fault exists and the secondary arc observed after the circuit breakers trip\([4]\). By ignoring the arc elongation, the primary arc can be considered to exhibit an approximately linear process for large currents. The secondary arc elongation causes an obvious nonlinearity\([5]\), reinforcing the complexity of the secondary arc. The arc model developed in a previous study\([6]\) was successfully applied to transmission systems for digitally simulating the primary and secondary arcs of a single-phase arc grounding fault.

Several studies have investigated the dynamic process after ignition. The electric faults that cause cable tunnel fires need to be further studied. Therefore, in this study, a digital arc fault model is established for a 220-kV cable transmission system. The parameters of the arc model were acquired from experimental measurements to improve the accuracy of the arc fault model. Further, we investigated the arc extinction limits to determine the arc duration. The energy accumulating during the arc fault process will play an important role in future research.

2. Mathematical arc model

The dynamic process of the arc can be described based on the power balance between the electric input power and the heat dissipation power. Thus, based on the energy balance theory, the arc can be expressed as a cylindrical conductor, the conductance of which changes dynamically. The arc in the air is described by a differential equation of the arc conductance \(g\) as follows:

\[
\frac{dg}{dt} = \frac{1}{\tau}(G - g),
\]

where \(g\) is the instantaneous arc conductance, \(G\) is the stationary arc conductance, and \(\tau\) is the time constant of the arc.

The arc can be divided into two distinct stages: the primary arc and the secondary arc.

2.1. Model of the primary arc

The stationary arc conductance \(G\) is the arc conductance observed when the arc continues for a sufficiently long period under fixed external conditions. The stationary arc conductance of the primary arc can be evaluated as follows\([7]\):

\[
G_p = \frac{i_{\text{arc}}}{V_p l_p},
\]

where \(G_p\) is the stationary arc conductance of the primary arc, \(i_{\text{arc}}\) is the arc current, \(V_p\) is the arc voltage gradient, and \(l_p\) is the primary arc length.

The time constant of the primary arc can be calculated as follows:

\[
\tau_p = \frac{\alpha_p l_p}{I_p},
\]

where \(\tau_p\) is the time constant of the primary arc, \(I_p\) is the peak arc current of the primary arc, and \(\alpha_p\) is the coefficient (approximately \(2.85 \times 10^{-4}\)).

2.2. Model of the secondary arc\([8]\)

The stationary arc conductance of the secondary arc can be defined as follows:

\[
G_s = \frac{i_{\text{arc}}}{u_s},
\]

where \(i_{\text{arc}}\) is the instantaneous arc current, and \(u_s\) is the stationary arc voltage.

The stationary arc voltage can be defined as follows:

\[
u_s = \left(u_0 + r_0 \frac{i_{\text{arc}}}{l_{\text{arc}}}ight)
\]

\(i_{\text{arc}}\).
where $u_0$ is the constant voltage parameter per arc length, $r_0$ is the resistive component per arc length, and $l_{arc}$ is the time-dependent arc length.

The time constant of the secondary arc is inversely proportional to the arc length and can be defined as follows:

$$\tau = \tau_0 \left( \frac{l_{arc}}{l_0} \right)^{\alpha_s},$$

(6)

where $\tau_0$ is the initial time constant, $l_0$ is the initial arc length, and $\alpha_s$ is a coefficient in the range of: $-0.1$ to $-0.6$.

3. Single-phase arc grounding fault modelling

3.1. Parameters of the arc model

It is almost impossible to reproduce the arc process via simulation because of the randomness and complexity of the arc. The accuracy of the arc model can be improved using the parameters that can be obtained from measurements only. The arc parameters $u_0$ and $\tau$ can be obtained during certain periods of time based on the traces of the measured arc voltages and currents. By assuming that the parameters $u_0$ and $\tau$ remain constant within a half period, the above two parameters can be calculated as follows:

$$u_0 = \frac{\int_{t_2}^{t_1} |i_{arc}| \, dt}{\int_{t_2}^{t_1} g \, dt}$$

and

$$\tau = \frac{1}{u_0} \left( \int_{t_2}^{t_1} |i_{arc}| \, dt - \int_{t_2}^{t_1} g \, dt \right) \left( g(t_2) - g(t_1) \right)$$

where $g = i_{arc} / u$ is the instantaneous arc conductance, $t_1$ and $t_2$ are the time points in a half period, where $g(t_1) = g(t_2)$, and $t_1$ is the time point within a half period, where $g(t_1)$ becomes maximum.

Figure 1 shows the arc parameters calculated from the experimental data. The time constant was obtained from the experimental results as an average value of $\tau = 0.4$ ms. The initial arc length $l_0$ was considered to be the air gap length when the cable breaks down. The arc parameters used in the single-phase arc grounding fault across a 220-kV cable transmission system in case of the primary arc are as follows:

$$V_p = 15 \text{kV} \quad I_p = 0.1 \text{m} \quad I_p = 74.29 \text{kA} \quad \alpha_p = 2.85 \times 10^{-5}$$

Further, the arc parameters in case of the secondary arc are as follows:

$$u_0 = 0.9 \text{kV} / \text{m} \quad r_0 = 0.4 \text{ms} \quad l_0 = 0.1 \text{m} \quad \alpha_s = -0.5$$

3.2. 220-kV cable transmission system model

In this study, the transient process of the single-phase arc grounding fault on PSCAD was simulated. The 220-kV transmission system is shown in Figure 2. The studied system was supplied with an ideal 220-kV power source via a 100-MVA transformer to the distribution system. Considering the distribution characteristics, the cables in the studied system used the Bergeron model based on the distributed inductance and capacitance parameters and lumped resistance. The length of cable was a total of 20 km. The fault location was 10 km away from the junction of the cable and source. The fault phase and ground were connected by a time-varying resistance to simulate the arc fault. The stable operating system was in a 30% load state. The primary arc could be observed when the cable broke down at 0.1 s. Because of high currents in the primary arc period. The circuit breakers of the fault phase
tripped within 0.03 s because of high currents in the primary arc period. Then, it entered the secondary arc stage.

![Figure 1](image1.png)

Figure 1. The arc parameters $u_a$ and $\tau$ calculated based on the arc voltages and currents

![Figure 2](image2.png)

Figure 2. Configuration of the 220-kV cable transmission system

3.3. Arc fault simulation results

The simulation results are shown in Figures 3–6. The primary arc voltages and currents were stable. At this stage, the arc elongation could be ignored. The primary arc was extinguished as the circuit breaker tripped at $t = 0.13$ s.

![Figure 3](image3.png)

Figure 3. Arc voltage in case of the single-phase arc grounding fault

![Figure 4](image4.png)

Figure 4. Arc current in case of the single-phase arc grounding fault
The transient pulses launched by the tripping of the circuit breaker could be observed when the secondary arc current was initiated, which reached a maximum value of 49.5 kA. Then, the secondary arc currents were restricted to a low value. As shown in Figure 5, the secondary arc voltage exhibited obvious nonlinear characteristics. The high-frequency components of the secondary arc voltages distorted the waveform to obtain an almost square wave. The most significant difference between the primary arc and the secondary arc was the arc elongation. The secondary arc voltage continued to increase with the increasing arc length. The secondary arc extinguished by itself with the increasing arc length.

3.4. Energy of the arc fault

The arc power should be analysed to study the thermal effect of the single-phase arc grounding fault. The input electrical energy will dissipate into the surroundings through heat conduction, heat radiation, and heat convection. The heat generated by the aforementioned process will result in a major risk of tunnel fires. Figure 7 shows the arc power of the primary and secondary arcs. Although the arc duration was only 0.03 s, the power of the primary arc was more than 1000 MW. The secondary arc power was consistent with the voltage variation tendency, which exhibited a continuously increasing trend.

The secondary arc did not extinguish until the dissipated energy became greater than the input energy. The extinction of the secondary arc is a complicated process because it is influenced by many factors. To calculate the extinguishing time of the secondary arc, some limits are introduced:\[9\]:

\[
\frac{\max \left( \frac{dr}{dt} \right)}{l_{arc}} = 20M\Omega / s \cdot m \quad \frac{g_{\text{min}}}{l_{arc}} = 50\mu S / m.
\]

The arc simulation results showed that the secondary arc extinguished at \( t = 0.69 \) s. The accumulated energy generated by the arc is presented in Figure 8. Considerable energy was produced by the primary arc in a short time. The energy generated by the secondary arc was obviously much smaller than that generated by the primary arc; however, it slowly increased before the arc extinguished. The accumulated energy in case of the arc fault in the 220-kV cable transmission system could eventually reach 4891 kJ. Such a large amount of energy will pose a hidden threat to the safety of the cable tunnels.
4. Conclusions

In this study, a digital arc model based on cybernetics was established to simulate a single-phase arc grounding fault for a 220-kV cable transmission system. The parameters acquired from the experimental data and empirical data improved the accuracy of the arc model. The characteristics of the arc were obtained by calculating and analyzing the primary and secondary arcs. The obtained arc energy provides a basis for performing further fire risk analysis.

The primary arc model has been built on empirical parameters. Apart from the arc elongation, the primary arc has stable characteristics. The secondary arc is initiated as soon as the circuit breakers trip. A large pulse related to the action time can be observed in the arc at the moment of tripping, and the peak of secondary arc currents can reach 49.5 kA. Secondary arc currents are not related to the increase in arc length and are restricted to a low value. The secondary arc voltages keep increasing with the increasing arc elongation and have nonlinear characteristics. Similarly, arc power exhibits an increasing trend.

In addition to arc power, another significant factor with respect to the energy generated by the arc is the arc duration. The duration of the primary arc is 0.03 s which depends on the action time of the relay protection system. According to the existing limitations of the secondary arc extinction, the arc fault will be eliminated 0.59 s after the occurrence of a fault. Thus, the energy accumulated during the entire fault can eventually become 4891 kJ. As the source of cable tunnel fires, the arc fault simulation enhances our understanding of the cable fire mechanism.

Acknowledgments

The authors gratefully acknowledge the support of The National Key Research and Development Program of China(2016YFB0900704) and Xi’an Power Supply Bureau (SGSNXA00JS1901470).

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