Fault Diagnosis of Transmission Lines Based on High Frequency Electromagnetic Spectrum Distribution Characteristics

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Abstract. According to the recognition of the fault of the transmission line, the traditional methods of manual detection, image recognition and infrared observation can not distinguish the defects, but at this time the line produces the electromagnetic interference level change is its produces the flaw the important characteristic. Therefore, the electromagnetic interference (EMI) can be used as a parameter in the inspection of high-voltage transmission line. This paper studies the correlation between the fault of the transmission line and the distribution of the high frequency electromagnetic spectrum, by analyzing the level change of the electromagnetic interference between the normal wire and the broken wire, the defects such as the old wire, the broken wire and the serious corrosion, which can not be distinguished by image, are detected, it provides a strong technical support for the condition assessment of transmission line conductors.

1. Introduction

With the development of national economy, the demand for electric power is higher and higher in the course of modernization construction, and the requirement for safe operation of electric power system is higher and higher. High-voltage transmission lines may be broken, damage, if not handled in a timely manner, will be broken in the vicinity of the broken wire in the case of rapid strain, broken or even short-circuit, resulting in the interruption of business data, large-scale blackout and loss of equipment and personnel and other serious consequences [1-2]. Therefore, it is necessary to test the broken and damaged high-voltage transmission lines to ensure the safety and reliability of transmission lines and the normal operation of power equipment.

When the transmission lines are damaged or seriously corroded, the traditional methods of manual detection, image recognition and infrared observation can not distinguish the defects [3-5], but at this time the line produces the electromagnetic interference level change is its produces the flaw the important characteristic. Therefore, the electromagnetic interference (EMI) can be used as a parameter in the inspection of high-voltage transmission line.

Based on the large-scale application of unmanned aerial vehicles (uavs) and the research on corona characteristics of transmission line conductors, this paper studies the correlation between the fault of transmission line strands and the distribution of high frequency electromagnetic spectrum, by analyzing the level change of the electromagnetic interference between the normal wire and the broken
wire, the defects such as the old wire, the broken wire and the serious corrosion, which can not be distinguished by image, are detected, it provides a strong technical support for the condition assessment of transmission line conductors.

2. Theoretical Computation of Electromagnetic Interference

For actual transmission lines, the Trichel pulse and the initial flow pattern appear in the negative half cycle and the positive half cycle under the operating field intensity. Both of these corona modes generate short-duration pulses of current with a steep rise time. The negative corona current pulse has faster rise time and shorter duration than the positive pulse, and the amplitude of the positive pulse is usually much higher than that of the negative pulse. Finally, the positive pulse becomes the main source of transmission line Ri.

Each corona discharge can be regarded as a current source, injecting a series of random current pulses into the wire. The injected current pulse can be divided into two pulses, each pulse has half the amplitude of the original pulse and propagates in the opposite direction along the wire. In the process of propagation, the pulses in both directions will be distorted and attenuated until they become negligible at a certain distance from the origin. Therefore, each corona source has only a limited observation distance depending on the attenuation characteristics of the line. Therefore, at any given point of a wire, the synthetic current is composed of pulses propagating in two directions from different sources distributed along the wire, the amplitude of the pulses changing randomly and the time interval distributing randomly.

In the time domain, the positive polarity corona pulse can be expressed as a double exponential:

\[ i(t) = K \cdot i_p \cdot (e^{\alpha t} - e^{\beta t}) \]  

(1)

Formula, \( i_p \) is the current amplitude (in Ma), \( K, \alpha \) and \( \beta \) are the waveform determined by the empirical constant, \( t \) units for ns.

Through the Fourier Transform, arbitrary time domain pulses \( f(t) \) and frequency domain \( F(\omega) \) can be correlated as follows:

\[ F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt \]  

(2)

\[ f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{j\omega t} d\omega \]  

(3)

In the formula, \( \omega \) is the angular frequency and \( f \) is the frequency, \( \omega = 2\pi f \). In general, \( F(\omega) \) is a complex function. For Real Function \( f(t) \cdot F(\omega) = F^*(\omega) \). Where \( * \) stands for complex conjugation. In this case, \( f(t) \) can be reduced to:

\[ f(t) = \frac{1}{\pi} \int_{0}^{\infty} |F(\omega)| \cdot \cos(\alpha t + \alpha(\omega)) d\omega \]  

(4)

Where \( |F(\omega)| \) is the amplitude and \( \alpha(\omega) \) is the phase angle of Frequency \( \omega \).

For Corona pulses defined by formula (1), the use of the Fourier transform can be described in the frequency domain as follows:

\[ F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt = \int_{-\infty}^{\infty} K \cdot i_p \cdot [e^{-\alpha t} - e^{-\beta t}] e^{-j\omega t} dt \]

\[ = K \cdot i_p \cdot \frac{\beta - \alpha}{(\alpha + j\omega) \cdot (\beta + j\omega)} \]  

(5)
Spectrum amplitude $|F(\omega)|$ is:

$$|F(\omega)| = K \cdot i_p \cdot \frac{\beta - \alpha}{\sqrt{\alpha^2 + \omega^2}} \cdot (\beta^2 + \omega^2)$$  \hspace{1cm} (6)

The maximum value of $|F(\omega)|$ appears at $\omega = 0$ as a function of the pulse amplitude and duration. $|F(\omega)|$ as a function of $\omega$ varies in different regions as follows:

$$|F(\omega)| = K \cdot i_p \cdot \frac{\beta - \alpha}{\alpha \beta}, \omega << \alpha, \omega << \beta$$  \hspace{1cm} (7)

$$|F(\omega)| = K \cdot i_p \cdot \frac{\beta - \alpha}{\sqrt{2 \beta \omega}}, \omega = \alpha, \omega << \beta$$  \hspace{1cm} (8)

$$|F(\omega)| = K \cdot i_p \cdot \frac{\beta - \alpha}{\sqrt{2} \omega^2}, \omega >> \alpha, \omega = \beta$$  \hspace{1cm} (9)

$$|F(\omega)| = K \cdot i_p \cdot \frac{\beta - \alpha}{\omega^2}, \omega >> \alpha, \omega >> \beta$$  \hspace{1cm} (10)

The value of $|F(\omega)|$ given by formula (7) at low frequencies (including Zeros) is actually equal to that given by formula (1), which gives the interval integral of the pulse waveform from 0 to $\infty$. As $\omega$ increases, the spectrum amplitude remains at this value until $\omega \to \alpha$. Then it starts to fall, almost inversely proportional to the frequency, as shown in (8). The second critical point occurs at $\omega \to \beta$, as shown in (9). The amplitude $|F(\omega)|$ begins to decrease inversely with $\omega^2$. At high frequencies, the amplitude is inversely proportional to $\omega^2$, as shown in (10). Therefore, the constants $\alpha$ and $\beta$ that define the pulse shape also define the transition point of the spectrum.

Taking the single corona source of corona discharge as a unit current section, the High Frequency Electric Field at the receiving point is calculated by using the antenna model of figure 1. The scale of the positive initial beam is about $\Delta l$, and the distance between the discharge point and the measuring point is $r$, the magnetic and electric fields at the measuring point can be calculated using equations (11) and (12):

$$\hat{H} = \frac{i \Delta l}{4\pi r^2} \cdot e^{-jk\omega} (1 + jkr) \sin \theta e_\phi$$  \hspace{1cm} (11)

\textbf{Figure 1.} Antenna model.
\[
\hat{E} = -j \frac{i \Delta l}{2 \pi \omega \varepsilon_0} \cdot \frac{e^{-jk} \cos \varphi}{r^3} (1 + jkr) - j \frac{i \Delta l}{4 \pi \omega \varepsilon_0} \cdot \frac{e^{-jk} \sin \theta}{r^2} (1 + jkr - k^2 r^2) \sin \theta _\varphi 
\] (12)

3. Test Analysis

In this test, the loop antenna is used to measure the EMI value. The test scheme is as follows: the length of the wire is 28m, the wire is pressurized to 63.5 kV, the EMI value of the intact wire and the broken wire is tested under the condition of 0.5 KHz. The simulation of a broken strand of wire is shown in figure 2.

**Figure 2.** Simulation of wire strand breakage.

![Figure 2](image)

**Figure 3.** Top view of point distribution.

![Figure 3](image)
Measurement point selection. $H = 2.95$ m; the simulated fault point is set as the midpoint of the wire; the origin is chosen to be 3.3 m away from the fault point on the ground projection, and the connection between the fault point and the midpoint is perpendicular to the wire.

The measurements were carried out with a spectrum analyzer, the first being a single broken strand of the analog wire under normal conditions and the second being a single broken strand of the wire. Each time 7 points were selected, respectively 2.5 m, 4.5 m to the right of the origin, 2 m, 3.8 m to the left, 1.7 m, 3.5 m, 5 m away from the traverse direction. A top view of the distribution of measurement points is shown in figure 3.

In the first measurement, the instantaneous value of radio interference at 0.5 Mhz under normal conductor conditions is obtained as shown in table 1. In the second measurement, the instantaneous value of the 0.5 MHz radio interference in the case of a broken conductor is obtained as shown in table 2. Two groups of data of normal and broken wires are compared, as shown in table 3.

Table 1. Instantaneous value of radio interference under normal conditions.

| Point position | 0  | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|----------------|----|----|----|----|----|----|----|----|
| Instantaneous value (dB·μV/m) | 47.8 | 50.6 | 49.4 | 48.6 | 50.0 | 45.2 | 43.6 | 44.5 |

Table 2. Instantaneous value of radio interference when the conductor is broken.

| Point position | 0  | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|----------------|----|----|----|----|----|----|----|----|
| Instantaneous value (dB·μV/m) | 58.0 | 51.4 | 53.1 | 51.7 | 49.1 | 46.7 | 45.5 | 45.3 |

Table 3. Comparison of instantaneous value of radio interference between normal and broken conductors.

| Point position | 0  | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|----------------|----|----|----|----|----|----|----|----|
| Normal conductor (dB·μV/m) | 47.8 | 50.6 | 49.4 | 48.6 | 50.0 | 45.2 | 43.6 | 44.5 |
| Broken Strand (dB·μV/m) | 58.0 | 51.4 | 53.1 | 51.7 | 49.1 | 46.7 | 45.5 | 45.3 |

The results of table 3 show that there is little difference in EMI between broken wires and intact wires at 4,5,6 and 7 points, and the longitudinal distance has little influence on EMI at 0,1,2 and 3 points, the difference of the electromagnetic interference between the broken wire and the intact wire is in the range of 3.1 ~ 10.2 dB(μV/m). With the change of the transverse distance, the electromagnetic interference will have some regular changes, therefore, the difference of EMI can be used to judge the broken strands of conductors.

4. Compute Validation

The main project to break the strands of wire as an example, see figure 4. It is assumed that the positive initial flux is the main contribution component of the electromagnetic interference in the AC corona discharge, and the amplitude of the pulse current is 20 mA in equation (1) , the single corona source of corona discharge is used as a unit current section to calculate the High Frequency Electric Field (0.5 MHz) at the receiving point by using the antenna model. The size of the positive initial beam is about 2 cm, and the distance between the discharge point and the measuring point is 8 m, using Equations (11) and (12) , the magnetic and electric fields at the measuring point are calculated.
Figure 4. Broken strand single point corona discharge and discharge scale.

In the calculation, the propagation attenuation of corona current on the wire is not considered, and it is an ideal free space, and the influence of the earth is ignored. Based on $1 \mu V/m$, the electromagnetic interference electric field is converted to $E(\text{dB}) \approx 58.31$ at 0.5 Mhz frequency. The calculated results are close to the electromagnetic interference value of 58.0 dB ($\mu V/m$) at 0.5 MHz.

5. Conclusion

Based on the analysis of the generation and propagation of electromagnetic interference (EMI) on transmission lines, combined with the characteristics of EMI on transmission lines, the EMI tests on normal and broken conductors of transmission lines are carried out, the experimental results are verified by theoretical calculation. The specific conclusions are as follows:

(1) At 4,5,6,7 points, the difference of EMI between broken wire and intact wire is small, and the longitudinal distance has little influence on EMI;

(2) At points 0,1,2 and 3, the difference of EMI between Broken and intact conductors is in the range of 3.1-10.2 dB ($\mu V/m$). With the change of transverse distance, there are some regular changes in EMI.

(3) According to the theoretical calculation, the value of electromagnetic interference at 0.5 MHz is about 58.31 dB ($\mu V/m$), which is close to the value of electromagnetic interference at 0.5 MHz ($\mu V/m$).

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