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# Two-point measurement approach to diagnostics of partly damaged insulator chains in high-voltage overhead lines

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**Abstract**. A system for location of fault insulator strings is proposed. Insulation failure in a defective isolator results in the occurrence of a significant current discharge in the circuit, which achieves some amperes and whose main own oscillation frequency is in the range of 15-30 MHz. The exact location of the defective string of insulators can be determined by aerial inspection with two small aircraft equipped with synchronized oscillographs which record high-frequency electromagnetic pulses. Processing of the recorded waveforms with geo tags makes it possible to locate a defective insulator string. The selection of the useful signal from the recorded waveforms is performed using wavelet analysis based on the main antenna characteristics. It was found that the accuracy of the location depends to a large extent on the characteristics of the instruments of the satellite exact time system.

## 1. Introduction

The modern world puts particularly high reliability requirements to the industries that are of great importance for the normal industry functioning and human life. The power industry is undoubtedly the basic industry which should be highly reliable. Insufficient electricity supply resulted from the disruption of the high-voltage overhead lines (HV OHL) can lead to large economic losses in industry. The analysis of OHL failures carried out in [1,2] shows that line isolation faults accounts for a significant part of all failures, therefore, timely and accurate location of the defects is an urgent problem. The physical reason for the occurrence of such a defect is a damaged glass insulator. Due to the influence of external factors such an insulator can lose its insulating properties, however, not completely. In practice, it is customary to call such insulators zero insulators, assuming that the remaining electric strength of this element is much less than the initial one. But the remaining reduced electric strength in the situation when the voltage distribution across the string of insulators is uneven, creates conditions when the damaged element can be blocked by a discharge along the surface of the remaining insulating part.

Currently, methods for inspecting overhead lines are divided into several groups [3-8]:

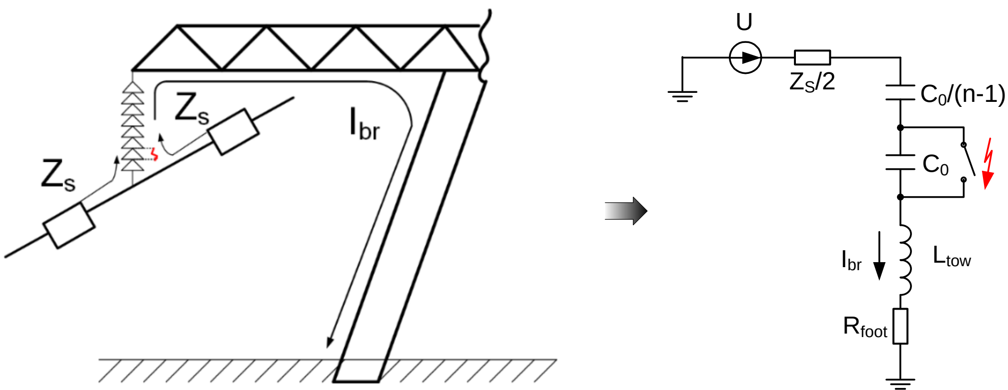
- visual and video inspection;
- thermal imaging control;
- acoustic monitoring;
- control by ultraviolet radiation;
- laser scanning of the line;
- analysis of electromagnetic radiation in the high frequency range.

In this work we propose a method based on the last group of methods - synchronous measurement and processing of high-frequency electromagnetic radiation at two points during a flight over an overhead power line using various small aircraft. For example, measurement information collection tools may be placed on board unmanned aerial vehicles (UAV).

## 2. Materials and Methods

### *2.1. Discharge processes caused by a defective insulator*

When the remaining electrical strength of the damaged insulator is small, the applied voltage is sufficient to cause a discharge along the surface of the remaining dielectric. This overlap is characterized by a high rate of current change, the frequency of which is determined directly by the current loop. To obtain an accurate measurement of the amplitude of the discharge current, the OHL support must be represented as line sections with different wave impedances for given frequencies, but such a solution of the problem entails large and complex calculations by means of the programs for calculating electromagnetic transient processes such as EMTP [9] or SPICE [10], which is not always justified. In this case we can use the engineering methodology for assessing the amplitude and frequency of the emerging current. It will be shown below that such an approach satisfies the accuracy of the process prediction at the moment of discharge. In this approach, the OHL support is substituted for a lumped inductance ($L_{tow}$), proportional to the sum of its element lengths - traverses and racks. The discharge current is limited by the phase wave impedance of the line at high frequency, the characteristic impedance of the discharge circuit and the tower footing resistance at high frequency. The current flow path and the equivalent circuit of the power line and discharge circuit are shown in Figure 1.




a) b)

**Figure 1.** The path of the HF discharge current (a) and the equivalent circuit for estimating the discharge current (b) (the support is represented by a lumped inductance).

At high frequencies, due to the weak penetration of the electromagnetic field into the earth (and, therefore, assuming that the soil resistance is ρ→0), the surge impedance of the power line conductor can be approximately calculated as

$$Z_S \cong 60\ln\left(\frac{2H}{r}\right), \quad r = \begin{cases} r_0, n=1 \\ \left(r_0 n r_b^{n-1}\right)^{1/n}, n \geq 2 \end{cases}, \quad r_b = \frac{a}{2\sin(\frac{\pi}{n})},$$

where $H$ - the average conductor suspension height, $r$ - the radius of the conductor ($r_0$ when $n$ = 1), or the radius of the equivalent conductor in case of a bundle conductor ($n$≥2); a - separation between sub-conductors; $n$ - a sub-conductors number.

The amplitude of the high-frequency discharge current, taking such a simplified model, is defined as

$$I_{\text{br.m}} = \frac{U_{\text{br}}}{\beta L_{\text{tow}}} e^{-\delta\pi/(2\beta)} \tag{1}$$

where $\delta = \dfrac{\frac{Z_C}{2} + R_{\text{foot}}}{2L_{\text{tow}}}$ and $\beta = \sqrt{\beta_0^2 - \delta^2}$ – oscillations decay factor and angular frequency, $R_{foot} \cong 100$ Om – tower footing resistance at a high frequency, $\beta_0 = \left(\dfrac{L_{\text{tow}} C_0}{N_{\text{ins}} - 1}\right)^{-0.5}$.

On HV OHL and especially EHV OHL, the discharge current is limited, to a greater extent, by the characteristic impedance of the discharge circuit ($Z_C$), which, in the general, is determined by the formula:

$$Z_{\text{C}} = \sqrt{\frac{L_{\text{tow}}(N_{\text{ins}} - 1)}{C_0}}.$$

With increasing operating voltage of the power transmission line, the number of insulators in the string ($N_{ins}$) increases, which leads to an increase in the characteristic impedance of the circuit $Z_{\text{C}}$. The high-frequency line impedance ($Z_{\text{S}}$) and the tower footing resistance at high frequency ($R_{\text{foot}}$) have a smaller effect on the current amplitude. Due to the relatively small attenuation ($Z_{\text{C}} >> (Z_{\text{S}}/2 + R_{\text{foot}})$), the amplitude of the discharge current can be estimated less accurately than (1) as

$$I_{\text{br.m}} \cong \frac{U_{\text{br}}}{Z_{\text{C}}} e^{-\delta\pi/(2\beta)}. \tag{2}$$

**Table.1** Characteristics of discharge circuit

| $U_{rated}$, kV | 110 | 220 | 330 | 500 | 750 |
|---|---|---|---|---|---|
| $Z_{\text{S}}$, Ohm | 450 | 460 | 360 | 330 | 315 |
| $Z_{\text{C}}$, Ohm | 1800 | 2800 | 3700 | 4600 | 6500 |
| $N_{\text{ins}}$ | 7 | 13 | 19 | 26 | 38 |
| $L_{\text{tow}}$, μH | 19 | 23 | 26* | 30* | 40* |
| $I'_{br.m}$, A | 4.8 | 3.3 | 2.6 | 2.1 | 1.5 |
| $F$, MHz | 15 | 19 | 22 | 25 | 26 |
| $I'_{\text{br.m}} F$ (A·MHz) | 79 | 65 | 58 | 50 | 37 |

*supports of the portal type (portal structure), the conductor is split; $r_0$ = 0.0104 m; $U_{br}$ = 10 $kV$

Table 1 shows the basic input data for the HV OHL, the calculated frequencies of natural oscillations and the approximate amplitudes of the discharge current, depending on the class of line voltage. In the calculations it was assumed that the intrinsic capacitance of the insulator is $C_0 = 35\ pF$, and the linear inductance of the support, depending on its design, is 0.8 - 1 $\mu H/m$ (a lower value for the portal type supports).

When analyzing the results presented in the table, it can be noted that the product of the initial discharge current ($I_{br.m}$) and the frequency $F = \beta/(2\pi)$ differs relatively little (approximately twice) from a change in the line operating voltage. This suggests that the EMF induced in the electromagnetic (EM) antenna of the device fixing the HF radiation will not depend heavily on the operating voltage of the high-voltage line.

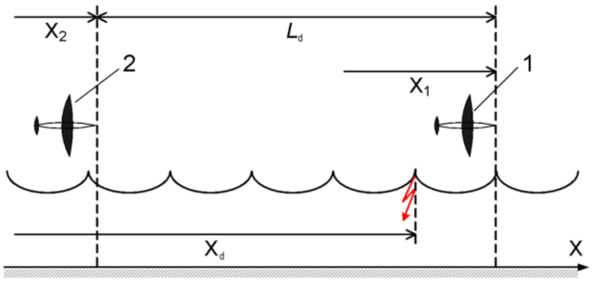
### *2.2. Location of the damaged string*

The methodology for determining a damaged element (an insulator in a string) is described in [11-14] and consists in recording EM radiation during a HV OHL inspection by aerial aircraft. The method involves the use of two registrars located at a certain distance from each other. When performing aerial inspection, they synchronously (through time synchronization receivers) register signals coming from the defective section (string of insulators) of the high-voltage power transmission line. During the flight, the additional data on their location is collected and registered, and for each captured waveform there is a reference to the place - a geographical tag. Next, the signal is processed using software that extracts pairs of waveforms taken at one moment in time from the data collected. When having the geo data for each waveform, it is possible to find out the distance between the two registrars and then analyze the recorded signals in order to accurately locate the defective string.

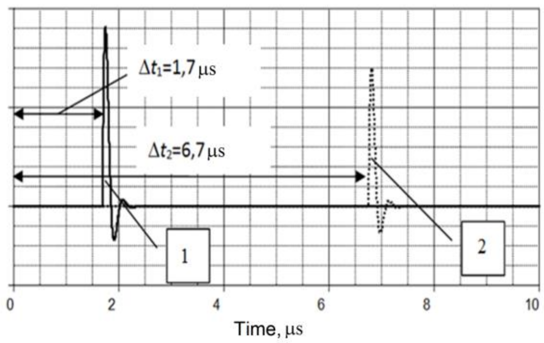
Table 1 shows the expected signal frequency (*F*), which provides useful information about the presence of a fault. When the emitted frequency is known as well as the characteristics of the receiving antenna and by using the methods of representing the signal in the frequency and time domain (window Fourier transform, wavelet transform), it is possible to find a signal that meets the search criteria. Such a criterion is the sum of the pulse occurrence times ($\Delta t_1$ and $\Delta t_2$) from the moment of simultaneous start of horizontal oscilloscope scans. This sum is the travel time of the electromagnetic wave to cover the distance between the two sensors - τ. It should be equal to the calculated wave travel time by using geotags. If this condition is met, then we can say that the defect is between two sensors and its coordinate is calculated by the expression

$$x_d = x_1 - \Delta t_1 v, \tag{3}$$

where $x_1$ is the “x” coordinate for the first sensor (i.e., the UAV), $v$ is the propagation velocity of the EM wave (for air, $v \cong 300$ m/us). An example of such a waveform in a simplified form is shown in Figure 2, *b*. It shows that there are two such signals caused by the breakdown of a zero/damaged insulator. By the delay time $\Delta t_1$=1.7 μs the coordinate of the fault on the line is determined.




a)




b)

**Figure 2.** The position of the aircraft during the aerial OHL inspection (a) and the pulses of electromagnetic sensors (b).

## 3. Results

To confirm the operability of this method, an experiment was conducted on the active 10 kV overhead line, on which an HF discharge was initiated. For these purposes, a cap insulator was suspended on a phase conductor, and an air gap with a breakdown voltage of 6 to 8 kV was connected to it in series (Figure 3). It acted as a defective insulator and, during breakdowns, generated high-frequency current pulses into a power line.

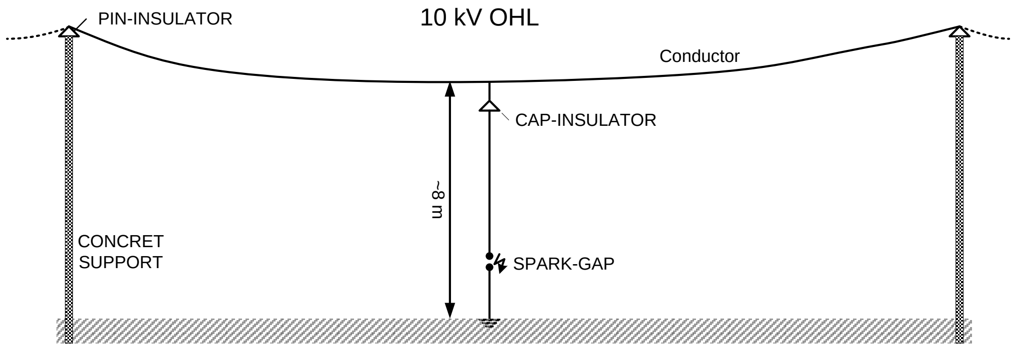



**Figure 3.** The scheme of the experiment.

Assessment of the current amplitude ($I_m$) can be performed by the expression (1), in which, instead of the support inductance, the inductance of the conductor connecting the linear wire to the ground electrode through an insulator and a spark gap should be taken. According to (1), for a conductor 8 m long, $C_0$ = 35pF, $H$ = 8 m, $R_{\text{foot}}$≅200 Om and $r_0$=6.9 mm, the current is in the range $I_m$ = 6.4 - 8.5 A. Due to the absence of high-quality artificial ground electrode in the middle span, the resistance $R_{foot}$ is a priori assumed to be of the specified value.

A current pulse flowing into the OHL conductor, as it spreads to both sides of the spark gap, induces a high-frequency electromagnetic field. During the pulses generation, an electromagnetic sensor was moving along the OHL, in the form of a square loop antenna with a side of 200 mm, located at a 1 m height from the surface of the earth. The signal induced in the sensor was recorded by a digital storage oscilloscope with a bandwidth of 100 MHz. The signal was recorded at several points: 200, 800, and 1000 meters from the HF radiation source. In addition, to simulate the real distance between the overhead power line and the aircraft, the sensor with the recording oscilloscope was separated by 35 meters from the line. The received signals were processed to determine the possibility of identifying points in time corresponding to the arrival of signals caused by breakdowns in the arrester. Waveform processing was carried out using wavelet analysis.

Analysis of the recorded signals using wavelets made it possible to accurately identify the main frequencies in the oscillations that occur in the measuring circuit, which included the inductance of the loop antenna ($L_{loop}$) and the input capacitance of the measuring cable ($C_{cab}$) and oscilloscope ($C_{osc}$). The calculated frequency of the natural oscillations of the measuring circuit was approximately = 16 MHz.

The frequency of the main oscillations formed during breakdowns of the air gap in the arrester is relatively small - about 8 MHz. However, the front of the current pulse introduced into the OHL is rather steep (~ 15 ns). Therefore, it is possible to assume that in the measuring frame located along the high-voltage line, an EMF of complex shape with a steep front is induced.

The high-frequency pulse was measured during a half-period of industrial frequency (10 ms) during which a breakdown of the discharge gap occurred. The total recording length was 10 million points, the time sampling step was 1 ns. Figures 4 shows fragment of oscillogram recorded at 200 m distance from the radiation source, and its spectrogram obtained by wavelet analysis [15]. Oscillations with a frequency of natural oscillations $f_0$ have the highest energy, they are exactly determined through wavelet analysis. The removal of the electromagnetic sensor at 35 m from the axis of the OHL path led to a weakening of the signal by approximately 10 dB. Without special signal processing algorithms for oscillograms it can be determined that the arriving time of the measuring pulse can approximately be considered the time of the first oscillation period occurrence with the fundamental frequency $f_0$. Based on this fact, the accuracy of fixing the time of pulse arrival to an electromagnetic sensor can be estimated at the period level of this frequency, i.e. $\sigma_{\Delta t} \cong 1/f_0$. For the loop antenna which was used $\sigma_{\Delta t} \cong 60$ ns, i.e. the geometric error is about 18 m. The average distance between adjacent HV OHL

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supports (span length) is about ~ 300 m, the travel time by the electromagnetic wave for this distance, respectively, is $\tau_{span}=1\ \mu s$. The estimated time error $\sigma_{\Delta t}$ is much less than the travel time ($\sigma_{\Delta t} << \tau_{span}$). Therefore, the assignment of a defective string of insulators to a specific HV OHL/EHV OHL support is carried out without error. However, it is necessary to take into account the limited accuracy of synchronization of the oscillograph system built on a satellite exact time system. The accuracy of the time synchronization system is about 100 ns, which results in the real maximum error in the location of defective insulation increase up to ~ 50 m.

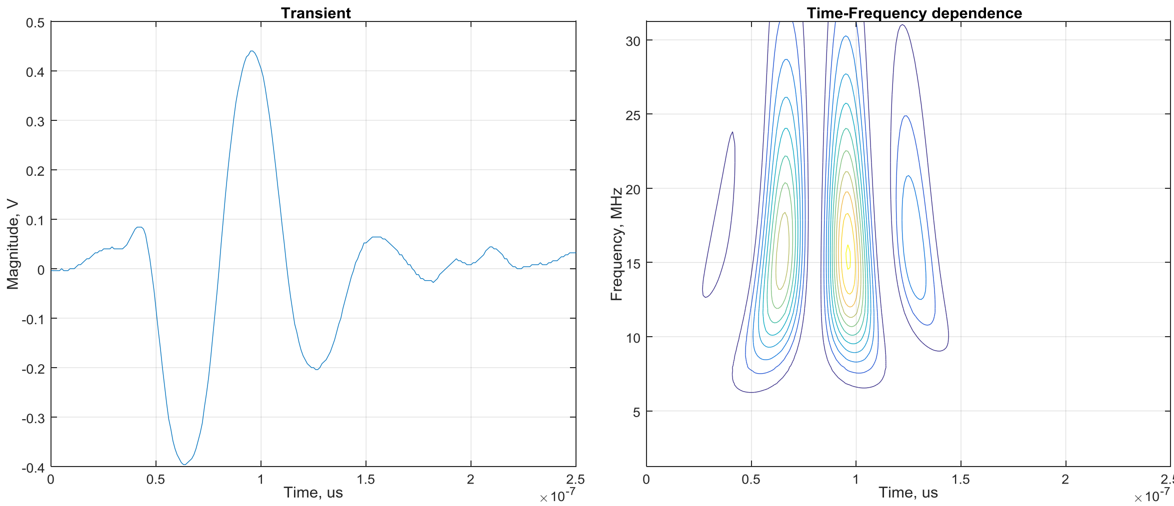


**Figure 4.** A waveform fragment for the voltage induced in the electromagnetic sensor (a) and the spectrogram obtained by using wavelet analysis (the distance from the sensor to the arrester is 200 meters, the location of the sensor is under the high-voltage line.

## 4. Discussion

It should be noted that the object where full-scale experiments on the discharge pulses generation were conducted and their registration at some distance from the radiation source (on an overhead power transmission line 10 kV) differs from the planned field of application - HV and EHV overhead power lines. The difference in the high-frequency signal propagation conditions can be explained by the fact that the 10 kV OHL supports are often located at small distances from each other - the distance between them is approximately 60 m. When high frequency pulse comes to each support with lumped capacity insulator on the reinforced concrete support having finite inductivity and earth resistance the pulse refraction occurs. On the HV and EHV lines, the distance between the supports is considerably greater (up to 300-350 m) and the signal refraction at the nodes is expected to be smaller. This has a positive effect on the signal propagation conditions and the possibility for its measuring. To estimate the signal propagation range of a similar (high-frequency / pulse) origin, it is planned to conduct an experiment on an overhead transmission line of 110 kV. It should also be noted that the developed method for locating defective strings can be used in any vehicles moving along the overhead lines routes.

## 5. Conclusion

1. It has been theoretically shown that during the damaged insulators breakdowns, a sufficiently large high-frequency current of Amperes (1.5 ... 5 A) is introduced into the line depending on the operating voltage of the high-voltage line.

2. Experimentally, on the active 10 kV line, the possibility of detecting high-frequency electromagnetic radiation similar to breakdowns of defective insulators is shown. The current level of measuring equipment development is quite sufficient for recording electromagnetic signals from defective insula-

tors at a distance of ~ 1 km. When using specialized low-noise amplifiers, this distance can be increased.

3. Determination of the useful signal associated with the moment of the defective insulator breakdown from the recorded waveforms is reliably performed using wavelet analysis.

4. The error in the location of defective insulation using the method described depends mainly on the characteristics of the exact time devices installed on aircraft.

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