SQUID-NDE of Wire Breakage in Aluminium Transmission Line

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Abstract. SQUID-NDE technique was applied to detection of wire breakage in aluminium transmission line, and aluminium clamp composed of compressed conductor joint. Hard aluminium transmission lines twisted from 19 aluminium wires with or without a wire breakage were prepared. While applying ac current of 2.6 mA at 200 Hz to the line, distributions of magnetic field gradient above the transmission lines were measured by a SQUID-NDE system using a HTS SQUID gradiometer. A periodic pattern was detected along the locus of broken wire in the distribution of the field gradient generated from the line with wire breakage, while such pattern was not observed in the normal line without wire breakage. Numerical simulation of distribution of field gradient from the aluminium transmission line was also carried out to compare it with the experimental results.

1. Introduction

Recently, there are some reports about serious issues regarding electrical and mechanical deteriorations of compressive conductor joints due to aging of the electric power transmission facilities [1, 2]. The compressive conductor joint is composed of aluminium transmission line twisted from a number of aluminium wires and aluminium clamp with a socket, where the transmission line is inserted in. The clamp is compressed to secure electrical and mechanical connection between the line and clamp. If the condition of the contact between them is bad, the contact surface is progressively oxidized due to aging. This deterioration causes an increase of contact resistance, and is quickened by heat generated by flowing currents, rain and damage from salt, and repeated stresses given by swing of the line due to breeze and stuck snow and ice. The increase of the resistance causes overheating in the connection part, and in the worst case, may result in the separation after melting and breakage of aluminium wires. In order to diagnose the integrity of the conductor joints, infrared thermal imaging equipments are used so as to identify the overheating points. Although this non-destructive evaluation (NDE) technique has the advantages such as high mobility, capability of remote running, and live-line diagnosis, it can only detect considerably high resistances, in other words, only progressed deterioration.

On the other hand, SQUID-NDE technique using high-\(T_c\) SQUIDs has successfully demonstrated the detection of deep-lying defects in conductors thanks to SQUID’s high sensitivity in low frequency
range [3-5]. In this study, we experimentally studied the application of SQUID-NDE technique to detect the wire breakage in the aluminium transmission lines. Simple numerical simulation was also carried out to compare its result with the experimental results.

2. Experimental setup

2.1. Specimens and NDE method
As a specimen, a hard-drawn aluminium transmission line (HAL) was selected from normal products, and aluminium clamp composed of compressive conductor joint (See figure 1). The HAL was twined from 19 aluminium wires of 3 mm in diameter, with total length of 250 mm and total diameter of 16 mm. The locus of each outer wire draws in a spiral, whose period is about 170 mm. The clamp has a socket in the cylindrical part with taper on the edge, where the HAL is inserted and then compressed. Because of the taper, stress is focused at the outer wires just under the taper. Thus, wire breakage occurs generally at this position. A fraction of 5 mm long in a wire was cut away to simulate wire breakage. For comparison, a normal HAL without wire breakage was also prepared. In this study, only the HALs with the wire breakage, which is not compressed with the clamp, were investigated.

To detect the wire breakage, current injection method was employed [6, 7]. It is supposed that when a normal HAL with flowing current would have wire breakage, the distribution of magnetic field from the HAL would be changed due to the wire breakage. Therefore, ac current was directly injected into all aluminium wires equivalently, and then two-dimensional distribution of field gradient was measured using a high $T_c$ SQUID first-order gradiometer to detect the wire breakage without requirement of magnetic shielding as shown in figure 2. Use of the gradiometer has also an advantage that it makes easy to estimate the current distribution in the HAL from measured field gradient distribution since the field gradient has similar distribution with the current flowing in a conductor [7].

2.2. SQUID-NDE system and measurement
We used the SQUID-NDE system for conductive materials as shown in figure 3. The detail of the system is described elsewhere [5-9]. Electromagnetically shielded room was used only to reduce the influence of radio-frequency waves. The specimen was set on the XY stage, and moved two-dimensionally in the x-y plane while measuring the distribution of field gradient by the SQUID gradiometer. In this case, sinusoidal current of total 2.6 mA at 200 Hz was injected in all wires of the specimens with or without wire breakage toward y-direction, and the gradiometer measured $dBz/dx$ (See figure 2). The minimum stand-off distance between the gradiometer and the top of the specimen was about 4 mm. The size of one pick-up coil and baseline of the gradiometer were 3.5 mm x 2.9 mm and 3.5 mm, respectively. The flux noise level of the SQUID gradiometer was about 60 $\mu$φ0/Hz$^{1/2}$, which corresponds to the field gradient noise level of about 6 pT/cm/Hz$^{1/2}$.

![Figure 1](image1.png)

**Figure 1.** Aluminium clamp (upper) and HAL with wire breakage and its cross-section (lower).
3. Results and discussion

3.1. Normal HAL specimen
The measurement results of a HAL specimen without a wire breakage are shown in figure 4. In the measurements, the distribution of field gradient \( \frac{dB_z}{dx} \) above the specimen was two-dimensionally measured first at 0 degree, (figure 4 (a)), and then the specimen was turned upside down, and again the distribution was measured at 180 degree, (figure 4 (b)), while injecting the same current. The photograph of the specimen at 0 degree is shown together in the upper region. Since the HAL line meanders a bit, the distributions of field gradients are not flat and correspond to the meandered shape in both cases. The local disturbances seen in the distributions are possibly due to the slight meander of the line and the resulting changes in the standoff distance between the gradiometer and the HALs and deviated wire density occurred in the process of twisting the wires.

3.2. HAL specimen with a wire breakage
The measurement results of a HAL specimen with a wire breakage are shown in figure 5. As well as the case of normal HAL specimen, the distribution of field gradient \( \frac{dB_z}{dx} \) above the specimen was measured at 0 degree, (figure 5 (a)), and then the specimen was turned upside down and measured again at 180 degree, (figure 5 (b)). The specimens are illustrated together with the locus of the wire with breakage and the cross-sections at different positions. Meander of the HAL specimen with wire breakage was somewhat less than that of normal HAL specimen. Compared with the results of normal HAL specimen, it is obvious that there is a certain pattern in the distributions above the HAL with wire breakage: the field gradient above the centre line of the HAL has lowest value at the position (A), where the locus of the wire with breakage located closest to the SQUID. The amplitude at the position (B), where the wire was farthest from the SQUID, is also small. In contrast, the amplitudes at the positions (C) and (C'), where the locus of the wire located just below the sides of the HAL, are larger than those at the other positions. This pattern has a periodic length such that the addition of the distances from left (C), through (A), (C'), (B), and to right (C) in figure 5 (a) (or from left (C'), through (B), (C), (A), and right (C') in figure 5 (b)) is about 170 mm, which corresponds to the period of the locus of the wire.

If we assume that current did not flow in the wire with breakage, these results can be explained as follows. The output of the SQUID gradiometer is affected mostly by the current density near the SQUID and the uniformity (or deviation) of the currents. The latter means that more uniformly or
(a) 0 degree. (b) 180 degree.

**Figure 4.** Measured distributions of field gradient above a normal HAL specimen.

**Figure 5.** Distributions of field gradient above HAL specimen with wire breakage. Locus of wire with breakage and the cross-section at different positions are depicted together.

(a) 0 degree. (b) 180 degree.

Symmetrically the currents distribute under the SQUID gradiometer, lower the SQUID output becomes, since the differential flux amount between two pick-up coil of the gradiometer becomes smaller above such currents [7]. It is estimated that the reason why the field gradient above the centre line of the HAL at (A) had smallest amplitude is because the current density near the SQUID at the position was less than those at the other positions as shown in figure 5. Additionally, that is also because the current distribution in the right-hand and that in the left-hand of the HAL were nearly symmetric. In the case of the position (B), the current density near the SQUID was apparently stronger than (A), whilst the right and left-hand current distributions were nearly symmetric as well as (A). These are the reason of
the small amplitude of field gradient at (B), which is a bit larger than (A). The largest amplitudes at (C) and (C’) are due to that the current densities near the SQUID were strong and the symmetries of the right and left-hand current distributions were most deviated. Therefore, the field gradient distribution above the HAL with wire breakage had such periodic pattern with period of locus of wire breakage. Also, it is indicated that when a wire is completely separated at one point, any current can not flow in the wire even though the wires have mechanical contact to each other.

4. Numerical simulation

In order to study the effect of wire breakage in the HAL and to compare with the experimental results, we simulated the distributions of the field gradients from a normal HAL and a HAL with a wire breakage by simple calculation. The HALs are modelled upon following assumptions:

- A HAL line is composed of 19 aluminium wires as the experimental specimens. Current can not flow in the whole length of a wire with a breakage. Equivalent current of 1 mA is injected in each wire with exception of a wire with breakage.
- Electric resistance between wires of HAL is supposed to be high enough to prevent currents flowing between wires, even though they have mechanical contacts. This is based on that the surface of aluminium line is easily oxidized in normal environments.
- Current injected in each wire is assumed to be line current in the centre of wire. In order to simulate the “twisted effect” of wires in the HAL, “rotating effect” is introduced as shown in figure 6. Each fraction of a wire is 7-mm long and the angle of each rotation is 15 degrees. In this case, the period of locus of a wire is about 168 mm.

To calculate magnetic field from the wires, the equation $B = \mu_0 I / 2\pi r$ was employed, where $B$ is magnetic field, $\mu_0$ is permeability of space, $I$ is infinite-long line current and $r$ is the distance between current and the measurement point. We assumed that all currents in the wires are parallel to the $y$-axis, and $B$ at a measurement point is only affected by the current distribution just below the point. Since the use of gradiometer was assumed, we calculated $B$ from each wire below a measurement point and add all $B$ from 19 wires at each measurement point, and then calculated $B_z$ component and $dB_z/dx$ from summed $B$. We consider neither the areas of pick-up coils nor baseline length. The standoff distance was set at 3 mm. Measurement points were set in $xy$-plane away from the top of the HAL models.

The calculated distributions of field gradients above the models of normal HAL and damaged HAL with wire breakage are shown in figure 7 (a) and (b), respectively. The HAL model with the locus of the wire with breakage and the cross-sections at certain positions is illustrated together. As shown in the figure 7 (a), the distribution of the normal HAL is flat in the $y$-direction. The amplitude of field gradient above the centre line is largest and constant. On the other hand, as shown in figure 7 (b), the amplitudes at the positions, where the locus of the broken wire locates at the top of the HAL, on the centre line of the HAL are lower than the other positions. The decreases of field gradient amplitude at these positions agree well with the experimental results. However, the decrease of amplitude above the positions, where locus of the wire with breakage locates at the bottom of the HAL, was not observed probably because the assumptions for this calculation must be too simple to simulate the accurate field gradient from the actual complex HAL more precisely.

Finally, it is summarised that it should be possible to detect a single wire breakage in the HAL using the SQUID-NDE technique by measuring the distribution of field gradient from the HAL lines and distinguish the periodic pattern in the distribution, which is the sign of a complete wire breakage.

5. Summary

The SQUID-NDE technique was applied to detect the wire breakage in the HALs. The periodic patterns due to the wire breakage were successfully observed in both the experiments and simulation. This indicates that it should be possible to detect a single-wire breakage in the HALs by distinguishing the periodic pattern in the distribution as the sign of a complete wire breakage. Next challenge is to know whether it is possible by the SQUID-NDE technique to detect hidden wire breakages in the transmission lines in compressed aluminium clamps.
Figure 6. Model of HAL line with wire breakage for calculation of field gradient distribution above HAL line.

Figure 7. Calculated distribution of field gradient above HAL specimen. HAL model and the cross-section at positions are depicted together.

(a) Normal. (b) With wire breakage.

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