Numerical Analysis of Breakage of Curved Copper Wires due to High Impulse Current

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Abstract—**In our past studies, we confirmed that thick straight copper wires of 1 mmϕ and over it were broken in a solid state before melting. The effect of physical damage on copper wire performance was confirmed. The test data suggest that ohmic heating is the main reason for thin (less than 1 mmϕ) copper wire breakage in the experiments. However, the magnetic force and skin effect are primarily responsible for breaking thick copper wires rather than thermal failure, as previously thought. When the thick curved copper wires were impressed by the lightning impulse current, they deformed into "heart" shape before they are broken. We used FEM software to simulate the deforming process when the curved copper wires carried the lightning impulse current. And the experimental and simulation results are in some degree agreement. Next we used the FEM software to analyze the temperature distribution of curved copper wires under heave current.**

Index Terms—**Breakage process, Lightning impulse current, Curved copper wires**

I. Introduction

Winter lightning strikes occur frequently over long periods in Japan's Hokuriku district. Moreover, high voltage and large current impart serious damage. This study specifically examines the properties of curved copper wires, which are used as lightning wires, under heavy current.

Here, we briefly present experimental results for curved copper wires from 0.3 mmϕ to 2.0 mmϕ while conducting heavy current. Then, we used the FEM software to simulate this deforming process and to analyze the temperature distribution of curved copper wires under heave current. Some thick curved copper wires deformed inside rather than out outside when they began to deform. The deforming process is that firstly the curved angle moved to the opposite direction; the curved part became flat, next because of the inertia effect, this part continually deformed to the opposite direction to the heart shape until it broke, suggesting that breakage occurred from the inner to the outer part at the curved part. The temperature on the curved part is higher than straight part. For copper wires of the same diameter, the smaller the curved angle, the higher the temperature is.

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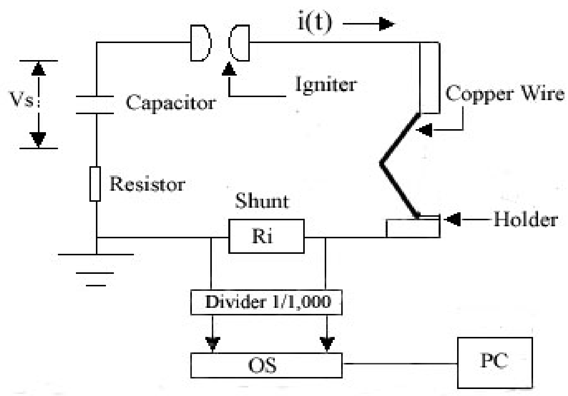


Fig. 1 Experimental circuit

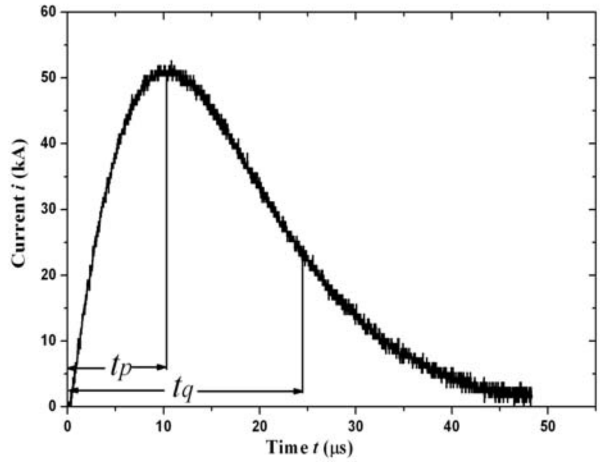


Fig. 2 Input impulse current (t_p=10 μs, t_q=24 μs)

II. Experimental Conditions

An impulse current generator (maximum voltage 160 kV; maximum stored energy 80 kJ; 32 capacitors each 2.5 μF, 40 kV), located at the Technical University of Munich, was used. The copper wire type was Cu-OF1 (purity > 99.95%; Gutmann Kabel). Figure 1 portrays the experimental circuit. The copper wires were bare and had a round cross-section. The effective wire length along the wire was L=0.82 m; the diameter was D=0.3–2.0 mm. They were fixed symmetrically to copper plate electrodes. The shunt resistance was R_i=2.7 mΩ; the voltage divider magnification was 1/1,000. The current wave shape *i(t)* was recorded using an oscilloscope (OS). The experiment was conducted at room temperature Θ_0 of approximately 15–18°C. The test current was a ca. 8/20 μs lightning impulse current presented in Fig. 2. Here t_p is the time to reach the peak current value I_p; t_q is the time for the current to fall to I_p/2.

III. Experimental Results

A. For 0.3 mmϕ and 0.6 mmϕ

For straight copper wires of 0.3 mmϕ and 0.6 mmϕ, after carrying the lightning impulse current, the copper wire was almost completely melted. Melted gems were formed at equal intervals along the wire. The straight thin copper wires of 0.3 mmϕ and 0.6 mmϕ were regarded to be almost completely melted. However, for curved copper wires of 0.3 mmϕ and 0.6 mmϕ, after conducting the lightning impulse current, breakage only occurred at the middle curved part; the broken tips became thinner, which was regarded as resulting from a tension force and melting. Furthermore, the total wire length was not elongated after it was broken.

B. For 1.0 mmϕ, 1.4 mmϕ, and 2.0 mmϕ

For curved copper wires of 1.0 mmϕ, 1.4 mmϕ and 2.0 mmϕ, after breakage by the lightning impulse current, the original curved shape was greatly altered by electro-magnetic force. Some took a heart shape. The breakage process of 1.0 mmϕ copper wire with a curved angle 90° is presented in Fig. 3. The copper wire was curved 90°, as in Fig. 3①, when the curved copper wire was not exposed to impulse current (0%*Ip*). With the input of lightning impulse current, the curved copper wire began to deform because of the electromagnetic force produced by its curved parts. The wire deformed into the shape shown in Fig. 3②, when lightning current with 94%*Ip* was carried by the curved copper wire. The copper wire deformed into the shape shown in Fig. 3③, when the lightning current with 99%*Ip* was input. After the lightning current with 100%*Ip* was input, the copper wire broke, as shown in Fig. 3④.

The breaking process was that first the curved angle moved to the opposite direction; the curved part became flat, next because of the inertia effect, this part continually deformed to the opposite direction to the heart shape until it broke, suggesting that breakage occurred from the inner to the outer part.

This breaking process was almost identical for all thick curved copper wires; breakage only occurred at the middle curved part. The broken tip became thinner and cone-shaped, suggesting that breakage arose mainly from tension and melting.

In Fig. 4, the measured breaking current peak values and theoretical adiabatic melting current peak values of copper wires with diameter of 0.3–2.0 mm are shown. The difference between measured breaking current peak values and theoretical adiabatic melting current peak values was very small for 0.3 mmϕ; however, this difference grew with increased diameter. Moreover, as shown in the figure, for copper wires of 0.3 mmϕ and 0.6 mmϕ, the curve angle had almost no influence on the breaking current peak values. They were broken by similar current peak values whether curved or straight. For copper wires of 1.0 mmϕ, 1.4 mmϕ, and 2.0 mmϕ, the curve angle strongly influenced the breaking current peak values. With the increase of the curve angle from the steeply curved to the straight, the breaking current peak value increased. It was readily apparent that electromagnetic force is the main reason for breakage of these thick copper wires. All breaking current peak values of thick curved copper wires were less than those of straight ones.

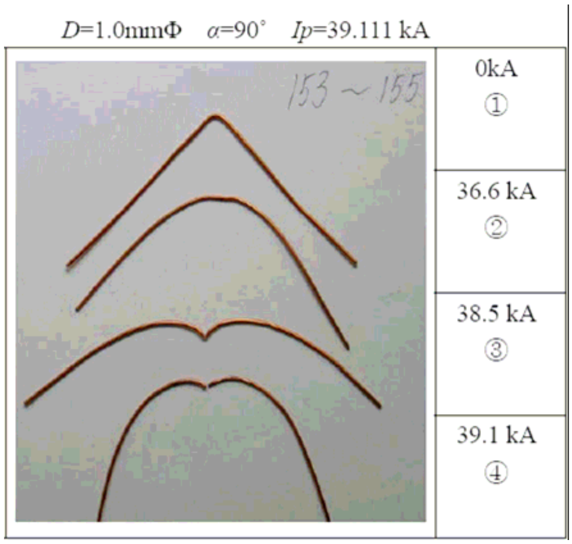


Fig. 3 Breakage process of curved copper wires

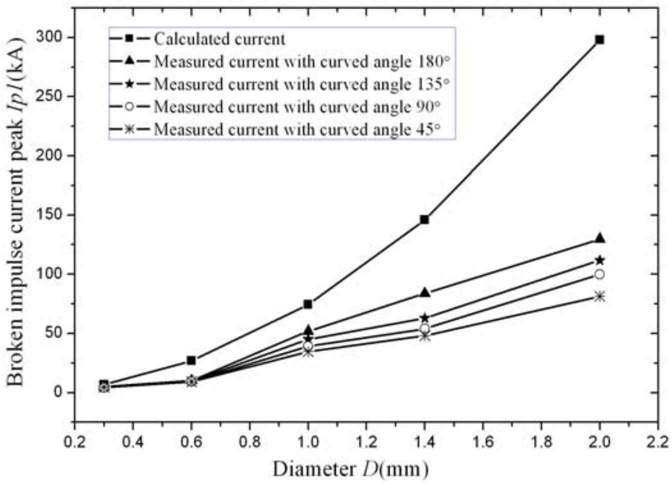
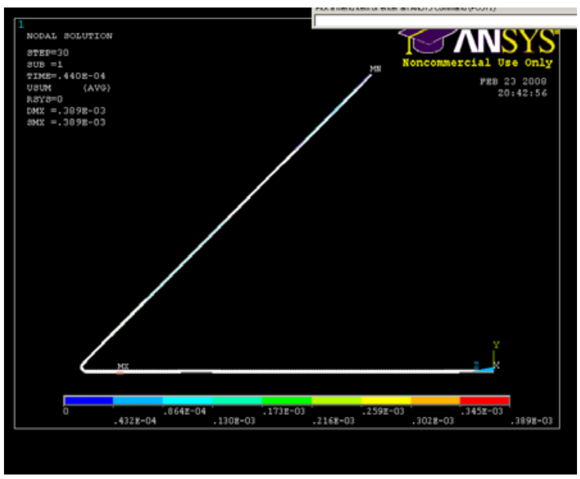


Fig. 4 Breakage characteristics of curved copper wires (impulse peak value versus diameter)



(a) Copper wire deformation at the 44th micro second (the ending time of impulse current)

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IV. Numerical Analyses

A. Electro-magnetic force

The Finite Element Method (FEM) software is used to simulate the curved copper wire's deformation process when they conducted the lightning impulse current.

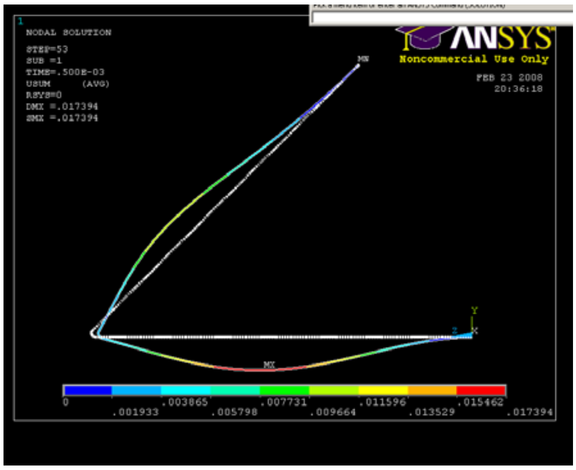
First, when the copper wire received the impact stress, the response time of the copper wire was investigated. Natural frequency of the copper wire was calculated and simulated by the FEM software about 64Hz~200Hz to 1.0mmϕ~2.0mmϕ, then comparing the natural frequency of the copper wires with the electro-magnetic force frequency ($f=1/90\times10^{-6}s=1.1\times10^{4}Hz$). Because the electro-magnetic force frequency was greatly faster than the copper wire natural frequency, the copper wire could not capture the frequency of electro-magnetic force. The curved copper wires should begin to deform after the lightning impulse current. With this fundamental physical condition, we used one-way coupling to analyse this process. That mean electro-magnetic force made copper wire to deform in the structural field, but the structural change did not affect the magnetic field and magnetic force distribution. Thus, there was no need to iterate between the magnetic field and structural field.

And the simulation results also proved this analysis process, the copper wire did not deform when the lightning impulse current finished at 44 micro second which was shown in Fig. 5(a). However the copper wire changed its shape after the impulse current finished, at 500 micro second it deformed into the shape shown in Fig. 5(b).

Secondly, we carried out transient magnetic analysis which is a technique for calculating magnetic fields that vary over time. In transient magnetic analysis, enough small area mesh is used to analyze eddy currents and magnetic forces induced by eddy currents which are shown in Fig. 6.

Fig. 7 showed significant skin effect when the copper wire initially carried the lightning impulse current.

Thirdly, we did transient dynamic structure analysis which is a technique used to determine the dynamic response of a structure under the action of time-dependent loads. Because the ultimate strength of the material changed greatly with high strain rate (μs order in the experiments), it was very difficult to determine the ultimate strength and elastic-plastic curve line of the copper wire with real experiments. Here we just considered the elastic effect, neglecting plastic effect and high strain rate effect. Fig. 8 showed the experimental result and simulation result, they are in great agreement. As shown in Fig. 8(b) with arrowhead, the curved part of the copper wire initially deformed to the opposite direction, then with inertia effect this part continually deformed to the opposite direction to the heart shape until it broke, which is same with the breaking direction of Fig. 3. Fig. 9 showed the stress distribution along the curved copper wire, as shown the inner part of the curved copper wire received the biggest stress and is easiest to be broken.



(b) Copper wire deformation at the 500th micro second (this time after the impulse current)

Fig. 5 (Curved angle α=45° Diameter D=1.0mm I_p=34.5kA)

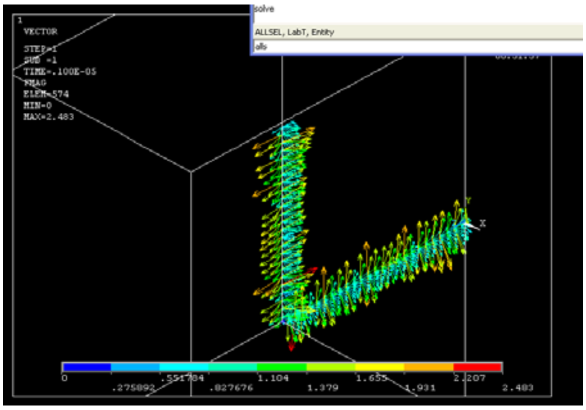


Fig. 6 Magnetic force distribution at the first micro second (Curved angle α=90° Diameter D=1.0mm)

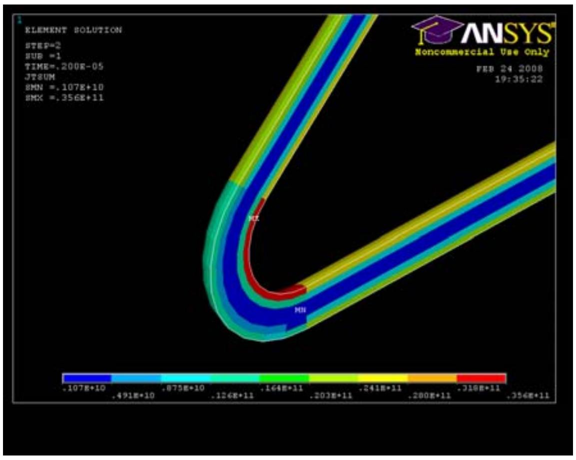
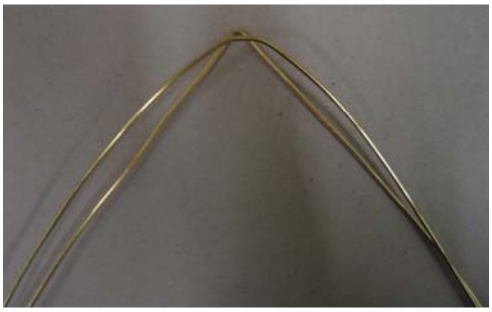


Fig. 7 Current density distribution at the second micro second (Curved angle α=45° Diameter D=1.0mm)



(a) Experimental result

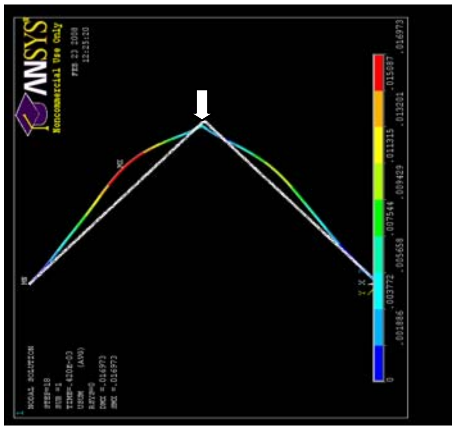


Fig. 8 (b) Simulation result
(Curved angle α=90° Diameter D=2.0mm)

B. Temperature

A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Our objective is to find temperature distributions in the copper wires.

Thermal simulations play an important role in the design of many engineering applications, including internal combustion engines, turbines, heat exchangers, piping systems, and electronic components. In many cases, engineers follow a thermal analysis with a stress analysis to calculate thermal stresses (that is, stresses caused by thermal expansions or contractions).

Here, according to the simulation formula, in our case if we want to capture 1μs temperature change, we must mesh the copper wire with 18e-6m. It needs huge memory. Here we just pay an attention to the temperature distribution not the exact temperature.

Because of the high frequency of the lightning impulse current, a markedly higher current density is expected to pertain at the copper wire surface initially (skin effect) when the copper wire was subjected to the lightning impulse current. Because the temperature is proportional to the current density, this initially higher surface current density produced a higher temperature at the copper wire surface layer shown in Fig. 10. When the copper wire diameter increased, the skin effect became more noticeable because the skin depth was only decided by current wave shape. With the same current wave shape (same angular frequency), the skin depth was the same. The thicker the copper wire, the higher the current density and the higher the temperature of the copper wire surface was.

Furthermore, the initial skin effect might cause diameter constriction by concentrating the current at the surface of the wire, which in turn strengthens their mutual attraction.

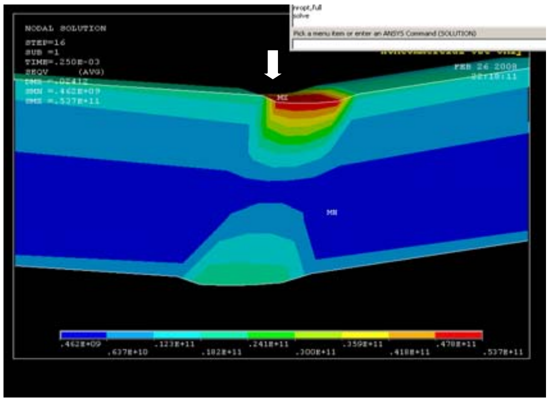


Fig. 9 Stress distribution along the copper wire
(Curved angle α=135° Diameter D=2.0mm)

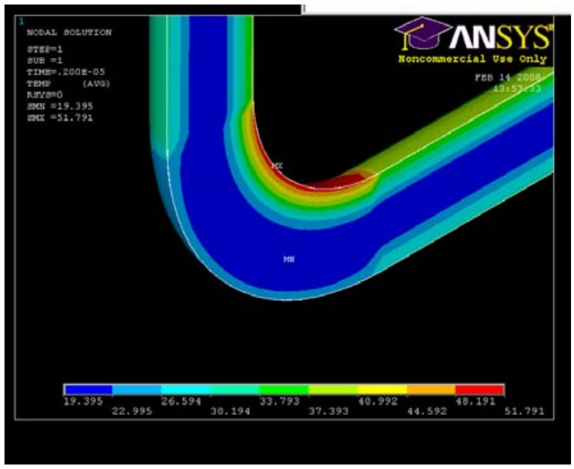


Fig. 10 Temperature distribution
(D is 1.0mm, curved angle is 90°)

V. Conclusions

The phenomena that straight and curved copper wires were broken by lightning impulse current were examined experimentally and theoretically, and the following results were obtained:

1) Copper wires, when broken by lightning impulse current, were broken in a solid state before melting.
2) A skin effect was noticeable when the copper wire carried the lightning impulse current.
3) Regarding curved copper wires, the curve angle had almost no influence on breaking current peak values for 0.3 mmϕ and 0.6 mmϕ. They were broken at almost equal current peak values whether curved or straight. However, the curve angle strongly influenced breaking current peak values for 1.0 mmϕ, 1.4 mmϕ, and 2.0 mmϕ; with increased curved angle from the steeply curved to straight, the breaking current peak value became larger.
4) The breaking process of the thick curved copper wires was that first the curved angle moved to the opposite direction; the curved part became flat, next because of

inertia effect this part continually deformed into the opposite direction to the heart shape until it was broken. This process suggests that breakage occurred from the inner part to the outer part to the curved part.

5) The inner curved part received the biggest stress and is easiest to be broken during the breaking process.
6) Results show that thin copper wires, less than 1 mmϕ, broke mainly because of ohmic heating. However, magnetic force and the skin effect, rather than thermal failure, were primarily responsible for breakage of thick copper wires.

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