著者（英） | 渋谷哲士, 坂野慶堂, 西村正広, 毛曽亮, 竹澤秀明, 中村貞彦, 山本優, 酒井豪, 佐川浩

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Investigation of Diode Rectifier Trouble by Lightning in D.C. Traction Substation

Hitoshi Hayashiya, Keiichiro Hanaoka, Kazumi Nishimura, Tomofumi Momose, Hideaki Takizawa, Takehiko Nakamura
Railway Operation Headquarters / Nagano Branch
East Japan Railway Company (JR East)
Tokyo, JAPAN

Yusuke Yamamoto, Kohei Sakaguchi, Shinji Yasui
Department of Computer Science and Engineering
Nagoya Institute of Technology (NIT)
Aichi, JAPAN

Abstract—On August 17th, 2012, a diode rectifier at Nagano Traction Substation was broken. The broken rectifier was dismantled and investigated in detail and, as a result, it was estimated that the overvoltage caused by the thunder lightning caused the dielectric breakdown in the rectifier. To confirm the assumption of the broken process, the field measurement at Nagano Traction Substation and FDTD (finite-difference time-domain) calculation analysis at Nagoya Institute of Technology were carried out. As a result, it was indicated that the direct lightning to the elevated bridge over the substation caused the transient overvoltage of the grounding system of the substation and resulted in the breakdown within the rectifier. Because the concrete bridge pier is located adjacent to the substation, the surge voltage from the elevated bridge is able to influence on the potential of the substation mesh. In this paper, the investigation process to determine the cause of the trouble will be shown in detail.

Keywords-component; traction substation, diode rectifier, railway, thunder lightning, grounding, FDTD, VSTL

I. INTRODUCTION

In August and September, 2008, we experienced severe lightning around Tokyo area and public services such as power supply and railway transportation were severely influence by them. Based on our experiences, the troubles in traction power supply system and railway signaling system caused by thunder lightning were investigated and evaluated [1], and some countermeasures against thunder lightning have been carried out since 2009 [2]. For example, the grounding system was improved mainly at traction substations of d.c. electric railway around Tokyo metropolitan area. More specifically, the length of grounding wires of surge arresters were made to be as short as possible to make surge impedance of the grounding wire small, as one of the countermeasures in traction substations [3], [4]. In catenaries system which is the overhead power supply system for railway operation above the railroad tracks, the most important issue caused by the thunder lightning is the continuous d.c. grounding fault current at the flashover point which results in the breaking of wire in some cases [5]. Because the grounding fault current in d.c. traction power supply system is much smaller than that of the nominal load current, the detection of the grounding faults is very difficult.

Some new approaches to detect the d.c. grounding fault is investigated and tested [6], [7].

Since 2009, the number of severe lightning troubles in East Japan Railway Company tends to be decreased. It is difficult, however, to say that it is by virtue of the countermeasures we had carried out, because only 7 years has passed and it is too short to evaluate the effect of the countermeasures statistically. We hope, however, that our countermeasures contribute to enhance reliability of traction power supply system.

In this paper, one of the major lightning troubles which happened on August 17th in 2012 at Nagano traction substation is discussed. Nagano Substation located far from Tokyo and the countermeasures of grounding system improvement was not applied.

In this trouble, a diode rectifies were broken by lightning. The outline of the trouble, the results of dismantle at the factory, the assumption of the cause of the trouble, the confirmation test to check the validity of the assumption at the field and the evaluation of the phenomena by computer simulation based on the FDTD method will be shown in this paper.

II. OUTLINE OF THE EVENT AND INITIAL INVESTIGATIONS

A. Outline of the event

About the lightning troubles in traction substation, two major troubles happened after 2008. One is a trouble of rectifier at Sakaori traction substation on July 25th in 2010 which was already reported in Ref. [8], and another is a trouble of rectifier at Nagano Substation on August 17th in 2012 which was firstly reported in Ref. [9]. In this paper, the procedure of cause investigation and dedicated assumption will be discussed.

Figure 2 shows the skeleton diagram of Nagano Substation and the broken rectifier is indicated as a shadow hatching box in this figure [9]. When the rectifier was broken, a lot of thunder lightning strokes were observed around the substation and it was estimated that the breakdown of the rectifier was caused by lightning. The location of the rectifier was, however, under the elevated bridge for the high speed railway and the electric machines of Nagano Substation for conventional
railway was completely shielded from lightning as shown in Figure 2 [10], and the electric machines of Nagano Substation are electrically independent from the catenaries system for high speed railway on the elevated bridge. The grounding down conductor of grounding wire on the elevated bridge is, however, lead to the ground along the pier adjacent to the Nagano Substation.

Judging from such a location of the broken rectifier, the procedure of the breakdown was estimated as follows:

- A thunder lightning hit the overhead grounding wire of the catenaries for high speed railway on the elevated bridge.
- The lightning surge went through the down conductor in the bridge pier and was released to the ground.
- A part of the released surge influenced the adjacent grounding mesh of the substation and the rectifier was broken by the transient overvoltage of the grounding mesh.

B. Dismantle investigation

The broken rectifier was replaced to the backup rectifier and it was moved to the factory of the manufacturer for the dismantle investigation on August 27th, 2010.

Figure 3 shows the location of the damaged parts in the dismantled rectifier [10]. The detail around (A, B, D) in Figure 3 is shown in Figure 4. The damage conditions of each part were as follows:

A. Arcing spot was confirmed on the ceiling board whose diameter is about 10mm. It was about 150mm above the top of the second radiator from the right, location B.

B. Dissolved losses were observed at the top of the 2nd radiator, those were the erosion of the corner of the radiator fin (B1) about 5mm, the melting and lacking of the screw of the bonding wire (B2) which connected 9 radiators, and the melting about 20mm at the top of the 2nd heat-pipe (B3) from the right.

C. Melting of the screw of the bonding wire was observed at the top of the leftmost radiator same as location B2.

D. Melting was observed at the top of the rightmost heat-pipe same as location B3.

E. Breakdown was detected at the insulation board between the diode and the grounded panel. The grounded panel was connected to the bottom of the 2nd heat-pipe.

According to the condition and the locations of the melting parts, the procedure of the fault was assumed to be as follows:

(Step1) The thunder lightning stroke the grounding wire or structure of the elevated bridge of high speed railway and the surge current went down to the ground via bridge pier adjacent to Nagano Substation. Some parts of the grounded current influenced on the potential of the substation for conventional railway under the elevated bridge.

(Step 2) The potential of the grounding system of the substation was enhanced because of the surge from the elevated bridge. It resulted in the breakdown at the insulation board between 750V of 12 pulses diode rectifier and the grounded heat-pipe (E). The grounding fault continued about 500ms before being detected by grounding fault relay and the grounding current flew from 2nd heat-pipe to rightmost and leftmost heat-pipes via bonding wires (B to C and B to D). The estimated current flow in circuit diagram is described in Figure 5.

(Step3) Because of the imperfect contact at the top of the heat-pipes, some parts (B2, B3, C, D) are heated because of the grounding fault current and melted.

(Step4) As a result, lastly, the screw head of the bonding wire melted (B1) and the bonding wire was flicked upward because of the electromagnetic force.

(Step5) Because the grounding fault continued flowing, the arc occurred between the edge of the fin (B1) and the flicked screw head and the screw head reached to the ceiling board (A) and the arc between the fin (B1) and the ceiling board (A) continued until the protection relay detected the fault.
C. Component analysis

The component analysis of the burned and melted part of the damaged equipment was carried out by EPMA (Electron Probe Micro Analyzer) analysis. The results are shown in Table 1.

Table 1. Results of component analysis

<table>
<thead>
<tr>
<th>Part of analysis</th>
<th>Many quantity</th>
<th>Small quantity</th>
<th>Very small quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of the melted heat pipe (B3)</td>
<td>Sn</td>
<td>Cu, Al, Mg</td>
<td></td>
</tr>
<tr>
<td>Surface of ceiling board around the melting point (A)</td>
<td>Cu, Al, C</td>
<td>O, Al, Ti, Sn, Mg</td>
<td></td>
</tr>
<tr>
<td>Melting point of ceiling board (near A)</td>
<td>Al, Fe</td>
<td>Cu, Ni, Cr, etc.</td>
<td></td>
</tr>
<tr>
<td>Melted aluminum fin (B1)</td>
<td>Fe</td>
<td>Cr, Cu, O</td>
<td>Ni, Al, S, Mn, Sn</td>
</tr>
</tbody>
</table>

III. FOLLOWING INVESTIGATIONS BY FIELD MEASUREMENTS

A. Interference measurement between GW and mesh

To confirm the validity of our assumption in Chapter II, the interference between the grounding wire for high speed railway on the elevated bridge and the mesh system of the traction substation for conventional railway under the elevated bridge was measured by applying utility frequency, 60Hz current to the grounding wire. The location of the each grounding system and the measurement devices are shown in Figure 7 [10], [11].

As shown in Figure 7, 14A current was applied to the grounding wire on the elevated bridge and the voltages induced by the current at the applied point (GW, V_y) and at the mesh (EM, V_x) are measured. The interference ratio (IR) is defined as follows:

$$ IR = \frac{V_y}{V_x} \times 100 $$

(1)

The measurements were carried out on August 6th, 2013 and August 22nd, 2013. The measured interference between the grounding wire (GW) and other groundings (EM, E1, E2, E3,
F) are summarized in Figure 6. In this figure, the interference between the groundings of the elevated bridge (E1, E2) and the substation mesh (EM) are also shown. According to the measurements, 10% to 30% interference between GW and EM is possible at most.

![Figure 8. Interference between each grounding system](image)

**B. Surge transition measurement from GW to EM**

To measure the direct interference between GW and mesh caused by the surge voltage, lightning impulse was applied to the GW on the elevated bridge and the transient response of the potential at the grounding of the diode rectifier was measured. The measurements were carried out on November 11th, 2016 and the waveforms of applied voltage and current are shown in Figure 9. The waveforms of applied voltage to GW and induced voltage at the grounding of the rectifier are shown in Figure 10.

![Figure 9. Waveforms of applied voltage and current to GW](image)

![Figure 10. Waveforms of applied voltage to GW and induced voltage at EM](image)

As shown in Figure 10, the induced voltage at the grounding of the rectifier is about 15.3% of the applied voltage to GW on the elevated bridge. This result was well consistent to the interference measurement by applying utility frequency to GW shown in the previous section.

The time delay of the peak voltage between the applied and induced surge voltage was, however, much longer than the expected value. The distance from the applied point to the measured point is about 100m at most but the time delay was more than 2 micro second that corresponds to the distance more than 500m. The inductions on the measurement circuit and the voltage fluctuation of the reference potential have to be doubted as a reason of such an unreasonable time delay. It should be discussed again in the future.

**IV. FOLLOWING INVESTIGATIONS BY COMPUTER SIMULATIONS**

**A. Purpose of simulations**

To reduce the transient potential rise of the grounding system of traction substation, the enforcement of mesh configuration of the grounding system will be one of the solutions. In this chapter, the quantitative evaluations of the effect of the enforcement are carried out based on the FDTD calculation using VSTL REV 2.3 (Virtual Surge Test Laboratory Restructured and Extended Version) provided by CRIEPI (Central Research Institute of Electric Power Industry, Japan).

**B. Simulation model**

Figure 11 shows the detail grounding system of the substation. Outline of the grounding wire was modeled in VSTL. For example, the simplified model of the square of the broken line around the rectifier, “3” in Figure 11 was shown in Figure 12. The lightning surge current with 100kA, 10/350 micro second wave-shape was injected at point A in Figure 11.

The analysis field of the model was 70m in parallel direction with rails, 36m in vertical direction to rails and 30m in perpendicular direction, respectively. 20m under the ground surface was modeled and the grounding wires are 0.75m beneath the ground surface. The ground resistivity was set to be 50 ohm-m and the element size in FDTD calculation was 0.25m cube. Liao’s 2nd order absorb boundary conditions were applied to all boundaries in the model.

The enforced grounding models, “Model B” and “Model C” are shown in Figure 13.

**C. Simulation results**

The transient potential change at point 1 and 2 in Model A are shown in Figure 14. As shown in Figure 14, the potential rise near the diode rectifier is larger than that at point 2 because the configuration of the grounding mesh is dead-ended. To solve such a dead-ended configuration, Model B and Model C are proposed and the comparisons of the potential changes near the rectifier in Model A, B and C are shown in Figure 14.
1. Receiving equipment
2. Traction transformer
3. Diode rectifier
4. d.c. circuit breaker
5. Series reactor
6. Auxiliary transformer
7. Distribution transformer
8. Distribution circuit breaker

Injection point of lightning surge A

Figure 11. Modelled grounding system of the traction substation

Measurement point 1
Measurement point 2

Figure 12. Simplified grounding system model around the rectifier (Model A)

(a) Model B
(b) Model C

Figure 13. Enforced grounding system around the rectifier

Figure 14. Potential changes at point 1 and 2 in Model A

Figure 15. Potential changes at Point 1 in Model A, B and C

As shown in Figure 13, the peak potential rise at point 1 are reduced about 15% in Model B by enforcing the grounding configuration of Model A. The effect of further enforcement as shown in Model C is, however, only 2% reduction compared with Model B.

D. Second simulations

Introduction of bonding wire to realize equipotential is one of the general concept to enhance lightning-proof of equipment. In this section, the effect of the equipotential between pier of elevated bridge and grounding system of Nagano Substation was checked.

Figure 16 shows the calculation model. As shown in this figure, the influences of enforcement of grounding configuration around diode rectifier (“Enforcement”) and bonding between pier of elevated bridge and grounding of substation (“Bonding”) are evaluated. The surge current of 100kA, 10/350 micro-second, is injected to grounding pole A.

The voltage responses at measurement point at diode rectifier are shown in Figure 17. Case 1 is without “Enforcement” and “Bonding”, Case 2 with “Enforcement” and without “Bonding”, Case 3 without “Enforcement” and with “Bonding”, and Case 4 with “Enforcement” and “Bonding”, respectively. As shown in this figure, the “Bonding” between pier and grounding of substation resulted in the increase of transient voltage at diode rectifier because it increase interference between down-conductor from grounding wire on the elevated bridge and grounding of substation.
The outline of the rectifier breaking trouble caused by the lightning on August 17th, 2012 at Nagano Substation is summarized in this paper. Based on the results of the dismantle investigation of the broken rectifier, the procedure of the trouble was assumed. To confirm the validity of the assumption that the surge propagated from the grounding wire for high speed railway on the elevated bridge to the grounding system of substation for conventional railway under the elevated bridge, field measurements and simulation studies were carried out. As a result of the field test at Nagano Substation, it was confirmed that the interference ratio between the GW on the elevated bridge and the substation mesh was about 10-30%. After the field measurements, the computer simulations using VSTL based on the FDTD calculation were carried out to confirm the effect of the countermeasures to suppress the transient potential rise around the broken rectifier. The simulation results indicate that the enforcement of the grounding configuration can suppress the potential rise about 15%. The influence of bonding between piers of elevated bridge and grounding of substation was simulated. Supposing surge propagation from down-conductor from elevated bridge, “Bonding” resulted in the increase of transient voltage.

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