Cause Investigation of Diode Rectifier Trouble by Lightning in Traction Substation

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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 summer, 2008, we had a lot of lightning in Japan and public services such as power supply and railway transportation were 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, in traction substations, the grounding system was improved. More specifically, the length of grounding wires of surge arresters were made to be as short as possible, 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 [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 6 years has passed and it is too short to evaluate the effect of the countermeasures statistically.

In this paper, one of the major lightning troubles which happened on August 17th in 2012 at Nagano traction substation is discussed. 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. The procedure of our investigation is summarized in Figure 1. This is the mid-term reporting of our investigation.

Figure 1. Procedure of our investigation
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 traction substation on August 17th in 2012. In this paper, the procedure of cause investigation and dedicated assumption will be discussed.

Figure 2 shows the skeleton diagram of Nagano traction 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 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 traction substation for conventional railway was completely shielded from lightning as shown in Figure 3 [9]. The electric machines of Nagano substation are also electrically independent from the catenaries system for high speed railway on the elevated bridge.

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.

![Figure 2. Skeleton diagram of Nagano SS](image)

Figure 3. Installation condition of rectifier

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 4 shows the location of the damaged parts in the dismantled rectifier [9]. 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:

(Step 1) 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. 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).

(Step 3) 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.

(Step 4) 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.

(Step 5) 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.

To confirm the validity of the above mentioned assumption, especially assumption of (Step 1), the field test to confirm the interference between the grounding wire system on the elevated bridge for high speed railway and the grounding system of the traction substation 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 5 [10], [11].

As shown in Figure 5, 14A current was applied to the grounding wire on the elevated bridge and the voltages induced by the current at the applied point (GW, \( V_x \)) and at the mesh (EM, \( V_y \)) 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.

A. Interference measurement between GW and mesh

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 5 [10], [11].

Figure 5. Location of each grounding system and measurement devices

Figure 6. Interference between each grounding system
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 7. The waveforms of applied voltage to GW and induced voltage at the grounding of the rectifier are shown in Figure 8.

As shown in Figure 8, 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.

The validity of the measurement will be confirmed by performing the similar measurement again at Nagano traction substation in the future. The results will be also confirmed by the computer simulation on VSTL 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. These are the initial report of our evaluations and the details including the validation of the model will be shown in the future.

B. Simulation model

Figure 9 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 9 was shown in Figure 10. The lightning surge current with 100kA, 10/350 micro second wave-shape was injected at point A in Figure 9.

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 11.

C. Simulation results

The transient potential change at point 1 and 2 in Model A are shown in Figure 12. As shown in Figure 12, 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 comparison of the potential changes near the rectifier in Model A, B and C are shown in Figure 13.
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

Figure 9. Model grounding system of the traction substation

Figure 10. Simplified grounding system model around the rectifier (Model A)

Figure 11. Enforced grounding system around the rectifier

Figure 12. Potential changes at point 1 and 2 in Model A

Figure 13. 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.

V. CONCLUSIONS AND FUTURE PROSPECTS

The outline of the rectifier breaking trouble caused by the lightning on August 17th, 2012 at Nagano traction 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. In this assumption, it was necessary 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. 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%. Here, the surge propagation tests were also carried out but it is required to confirm the validity of the test results in the future. Lastly, 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 results will be also confirmed in detail referring to the measurements at the field.

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REFERENCES


