Improved Detection of Winter Lightning in the Tohoku Region of Japan using Vaisala’s LS700x Technology

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Keywords: winter lightning, lightning detection

The demand for both data quality and the range of Cloud-to-Ground (CG) lightning parameters is highest for forensic applications within the electric utility industry. For years, the research and operational communities within this industry in Japan have pointed out a limitation of these LLS networks in the detection and location of damaging (high-current and/or large charge transfer) lightning flashes during the winter months (so-called “Winter Lightning”). Most of these flashes appear to be upward-connecting discharges, frequently referred to as “Ground-to-Cloud” (GC) flashes.

The basic architecture and design of Vaisala’s new LS700x lightning sensor was developed in-part to improve detection of these unusual and complex flashes. This paper presents our progress-to-date on this effort. We include a review of the winter lightning detection problem, an overview of the LS700x architecture, a discussion of how this architecture was exploited to evaluate and improve performance for winter lightning, and a presentation of results-to-date on performance improvement following upgrades to the instrumentation.

During a 3+ week evaluation period following the upgrade, the LS network detected more than twice the number of CG strokes as the older IMPACT network (1,675 vs. 797). It also reported 594 cloud pulses. Most of the lightning was either near the west coast (Sea-of-Japan) or hundreds of km into the north-western Pacific. During the 2010 summer when lightning occurred within the interior of the network, the IMPACT LLS actually performed better than the LS network. We have recently confirmed that this limitation was rectified in July 2011 after increasing the gain of the LS sensor (due to the longer baseline distances), and installing formal released software (v1.6) in the sensors.

Table 1. November-December case summary for all six high-current strokes, although two of these strokes were poorly located. 97% of the possible 36 sensor reports were produced by this network. Algorithm refinements based in the analysis of these data, were implemented in a “reprocessed” dataset and resulted good location for all six high-current strokes, and 100% reporting by all sensors.

During the second evaluation period in November-December 2010, 27 high-current (>65 kA) cases were evaluated, 20 of which were classified as GC based on LEMP waveform analysis. The lobe data for these events were not reprocessed with the improved processing algorithm. Almost all LS sensors reported events associated with these high-current strokes. One-third of these reports were not sufficiently consistent to contribute to calculated locations. 25 of 27 (93%) of the strokes were located by the LS network, including 9/9 (100%) +GC and 10/11 (91%) −CG strokes. In three cases, the LLS provided poor peak current estimates, when compared to LEMP-based estimates. There were five cases where the LLS classified the strokes as cloud discharges. Table 1 below provides a summary of the November-December findings.

The algorithm updates employed in the reprocessing of the first evaluation period have been implemented in the upcoming release the LS sensor software. Future work will focus on small refinements to the detection algorithms, automatic classification of the various types of GC discharges, and refinement of peak current estimates for GC strokes based on evolving models.
Seasonal Variation of Frequency of High Current Lightning Discharges Observed by JLDN

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Keywords: lightning, winter lightning, upward lightning, LLS, high-current

On the coast of the Sea of Japan, many lighting discharges are observed even in winter. Features of the winter lightning are different from those observed in summer, namely, high current energetic strokes, flashes transferring large charge amount, positive strokes and upward lightning strokes are frequently observed. Besides, transmission line outages and damages to wind turbines are frequently experienced in winter.

Meanwhile, although most of the damages caused by winter lightning strokes are related to upward lightning discharges, the period when upward lightning occurs is not certain. Also, spring and autumn as transition periods between summer and winter are not certain. This classification is based on that lightning discharges in autumn or spring are relatively small in numbers and have been treated as unimportant. Serious transmission line outages caused by lightning, however, are occasionally reported in spring and autumn and features of lightning discharges in these periods are probably different from those in summer. Hence, characterizations of seasons and analysis of features of lightning in each season are carried out.

Seasonal variations of number of high current lightning discharges exceeding 100 kA observed by LLS (Lightning location system) were analyzed. Data from LLS named JLDN (Japanese Lightning Detection Network) have been analyzed. This system is operated by Franklin Japan Co.

Figure 1 shows monthly variation of number of high current lightning discharges in two areas of 120 km square, namely on the Pacific Ocean side and on the Sea of Japan side. Observation results are not affected by terrain of these areas. The monthly averaged altitudes of −10°C level are higher than 5.7 km irrespective of the areas in the months when the numbers of negative high current lightning discharges are larger than those of positive ones as shown in Fig. 1. Therefore, the months with averaged altitudes of −10°C level higher than 5.7 km can be classified as ordinary “summer” from the viewpoint of lightning activity.

Meanwhile, in Fukui area on the coast of the Sea of Japan, more than 90% of negative high current lightning discharges were negative Ground to Cloud (−GC) strokes in the months with monthly averaged altitudes of −10°C level lower than 2.7 km. These months can be classified as the winter lightning season when upward lightning flashes frequently occur. These altitudes of −10°C level, 5.7 and 2.7 km, are tentative, and can be adjusted after accumulating of data.

Months other than winter or summer are classified as spring or autumn. In these seasons, the ratios of positive high current lightning discharges are higher than those of the negative discharges like winter. Thus, the charge structure in the thunderclouds may be similar to that in winter, and high current lightning strokes tend to occur. The upward lightning rate, however, is lower than that of winter in spring and autumn.

Relationship of seasons and densities of high current lightning strokes exceeding 100 kA in absolute value are investigated at 9 areas, namely Ishikari, Aomori, Akita, Fukui, Tochigi, San-in, Kitakyushu, Kagoshima, and Okinawa areas. In each area, seasonality of months is identified based on the average altitude of −10°C level observed at an aerological observatory in the vicinity.

Altitudes of −10°C layers are different in each area, even in the coastal area of the Sea of Japan, that is, winter months when upward lightning discharges are frequently observed slightly differ depending mainly on the latitude. Thus, occurrence probability of upward lightning discharges likely depends on the lightning stroke density and the altitude of −10°C layer.
An Analysis of the Initial Breakdown Pulses for Positive
Cloud-to-Ground Flashes

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Keywords: initial breakdown pulse, positive cloud-to-ground flashes, distribution, polarity

Lightning is initiated by the initial breakdown process, followed by a quiet intermediate stage with little associated radiation. The pulse train, whose pulse is bipolar as usual, can be found in electric field waveform of the initial process due to the discharge that takes place inside the cloud between oppositely charged regions. As a main physical process of lightning, its research is of great benefit to reveal the origination and transmission of lightning discharge. However, in most of the publications, analyses are done only on pulse trains preceding negative return strokes. To the best of our knowledge, there is only few detailed information concerning the statistics of preliminary breakdown pulses preceding the positive ground flashes in previous literature.

In order to further understand the initiating mechanism of positive cloud-to-ground (PCG) flashes, the study will investigate the temporal characteristics of the PBP trains, of summer thunder storms in tropic regions. In order to simply depict, we term these electric fields negative breakdown pulse (NBP) trains if they precede negative return strokes, and positive breakdown pulse (PBP) trains if they precede positive return strokes.

The data with 79 fast electric field records of lightning discharges were used to analyze the initial breakdown pulse for positive cloud-to-ground (PCG) flashes. The measurements were conducted in Conghua of Guangzhou province (latitude 23.38N and longitude 113.35E), in the period of May–August in 2010. The electric field measuring system included a circular flat plate antenna followed by an integrator and a unity gain, high-input impedance amplifier. The antenna was installed on the roof of a three-story building at the weather bureau of Conghua.

In the research, the following parameters, including the width of individual pulse (T_{pw}), the duration of PBP train (T_d), the interval between the adjacent peaks of pulse (T_{pi}), the interval between RS and PBP train (T_{p-r}) and the ratio between the peaks of RS and PBP train (R_{p-r}), are analyzed. The possible causes of the observation of several types of pulse trains and the significantly diversified pulse characteristics of the breakdown pulse trains are discussed. The results are as follows:

1. According the statistical results, PCG flashes with PBP trains (the term ‘PBP flash’ used in the following description) are about 12% of all the PCG flashes. Considering the difference in attenuation factor between PBP and RS, the value of 12% is a lower estimation. PBP flashes have a large ratio in the interval with low amount of PCG flashes.
2. According to the difference in the relationship between initial polarity of PBP and initial polarity of RS, three types of PBP trains, the same polarity (type I), the opposite polarity (type II) and composite polarity (type III), are identified. For type III, the initial polarity in the two regions may be the same or opposite to the polarity of RS. The percentages of type I, II and III are about 84%, 10% and 6%, respectively.
3. The values of the pulse width T_{pw}, the train duration T_d and the pulse interval T_{pi} for type II are little than those of type I, however, the values of T_{p-r} and R_{p-r} are larger than that of type I. It is possible that the difference in discharge region lead to the difference. The different regions have different discharge distance, which may lead to different pulse parameters.
4. The ratio of the maximum peak amplitude of initial breakdown pulses to the amplitude of return stroke (R_{p-r}) with the value of 0.16 is smaller at Conghua in Guangzhou province than at Hokuriku coast in Japan and in Brazil, which perhaps may be attributed to the difference of storm characteristics.
5. The parameters of all PBP trains, including the width of individual pulse, the duration of the PBP train, the interval between the adjacent peaks of pulses, the interval between the RS and PBP train and the ratio between the peak of PBP train and RS are about 25 µs, 8.88 ms, 271 µs, 98.48 ms and 0.16, respectively.
Reproduction of Observed Electromagnetic Field Waveforms Produced by Winter Lightning

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Keywords: lightning, winter lightning, upward lightning, lightning current, electromagnetic field, lightning stroke model

The lightning current waveform of winter lightning is one of the most important parameters for lightning protection methods. The lightning current waveforms can be estimated from electromagnetic field waveforms by using a transmission line (TL) model assuming a return stroke. However, most of winter lightning flashes that hit transmission towers in the coastal area of the Sea of Japan are upward lightning flashes from the transmission towers. Therefore, the lightning stroke model for the upward lightning flash is needed to estimate the lightning current waveforms of winter lightning.

The positive lightning flashes initiated upward from a radio tower were observed in winter 2001. Figures 1 and 2 show the lightning current waveform and the electric field waveform respectively. Slow front and fast transition, which are common characteristics of the electric field waveform associated with all the return strokes, were not recognized clearly at the rising portion of the lightning waveform.

Two lightning stroke models were used to reproduce the observed magnetic field waveform. Figure 3 shows the lightning stroke model for the upward lightning. The calculated magnetic field waveform by using the upward stroke model, in which the current wave propagates downward from the cloud and reflects at the ground, agreed well with the observed waveform (Fig. 4). On the other hand, the peak value of the calculated waveform by using the return stroke model was larger than that of the observed waveform (Fig. 5).

If the usual return stroke model is used for the calculation of the upward lightning current waveform, the peak of the current waveform may be estimated smaller than that of an actual current waveform. This result shows that the upward lightning stroke model should be adopted for the accurate estimation of the current waveform of winter lightning.
Distribution Surge Arrester Failures due to Winter Lightning and Measurement of Energy Absorption Capability of Arresters

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Keywords: power distribution line, lightning, winter lightning, surge arrester, energy absorption capability, ZnO element

Surge arresters and/or an overhead ground wire (OGW) are used for lightning protection of overhead power distribution lines. In Japan, distribution equipments, such as insulators, pole-mounted transformers and switches, with zinc-oxide (ZnO) elements have been used in addition to the conventional surge arresters. The increase of surge arresters including distribution equipments with ZnO elements has resulted in a marked decrease of lightning outages of distribution lines due to sparkover. On the other hand, several surge arresters are damaged by direct lightning strokes, especially in winter. Winter lightning strokes have very large electric charge as compared with summer lightning. In winter, the proportion of damages of surge arresters to the total lightning damages was approximately 50% at maximum in the Hokuriku area, and also the number of surge arrester failures in winter was two times as large as that in summer recently. There are two methods for prevention against surge arrester failures: (1) installation of an OGW or a second OGW in addition to the conventional OGW, (2) improvement of the energy absorption capability of surge arresters.

For improvement of distribution surge arresters, we have measured the energy absorption capability of surge arresters using a half cycle of alternating current with a frequency of 50 Hz for simulating a winter lightning current waveform with a long duration of current. Six kinds of surge arresters with ZnO elements (A–F) were used for the experiment. These arresters were divided into two types by additive materials for ZnO elements: the elements containing bismuth oxide (Type I), the elements containing rare earth metal oxide (Type II). The mean values of arrester failure energy increased in proportion to the volume of ZnO element and the mean values of arrester failure energy per the volume of ZnO element were different from each other in type of additive materials. However, the values of arrester failure energy were quite uneven, the minimum value of arrester failure energy was twice or more the maximum value in some cases. We also have observed the aspects of damaged ZnO elements. The failure types of ZnO elements were classified into four types: (a) cracking, (b) flashover on side by puncture on terminal, (c) flashover on side by chipped edge, as in Fig. 1, and (d) change of reference voltage with normal externals. The relationship between the mean values of arrester failure energy and the failure types of ZnO elements has been investigated. In the case of “flashover on side by chipped edge”, the mean values of arrester failure energy were smallest of four failure types of ZnO elements as in Fig. 2.

From these results, we suggest the improvement of the energy absorption capability of distribution surge arresters, especially for the uniform energy absorption capability. One method to improve surge arresters is enlarging the volume of ZnO element to increase the thermal capacity. The volume of the element can be enlarged by increasing the sectional area and/or the height of the element. Enlarging the sectional area of the element is more effective than increasing the height of the element for reducing “flashover on side by chipped edge” with small failure energy. Another method is the reinforcement of insulation strength on the side of ZnO element for reducing the unevenness of arrester failure energy. As the means, we propose thicker coating of side insulation, and wrapping the element with the insulation sheet.

Fig. 1. Aspects of damaged ZnO elements

Fig. 2. Relationship between mean values of arrester failure energy and failure types of ZnO elements
Characteristics of Upward Leaders of Winter Lightning in the Coastal Area of the Sea of Japan

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Keywords: upward leader, winter lightning

Upward lightning flashes generally occur at very tall structures or structures built in mountainous areas. There are many upward lightning flashes during winter in the coastal area of the Sea of Japan. Upward lightning flashes are initiated by the inception of upward leaders from grounded structures. The striking point of upward lightning is determined by the inception and propagation characteristics of the upward leader. Thus, it is necessary to understand the inception and propagation characteristics of upward leaders for protection against upward lightning strikes.

We observed the winter lightning flashes striking the chimney of the Fukui thermal power plant located in the coastal area of the Sea of Japan from 1989 to 2008. We used ALPS (Automatic Lightning Progressing feature observation System) and a high-speed digital video camera to measure the upward leaders. ALPS is an ultra high-speed digital camera system. Lightning current waveforms were measured using two shunt resistors (2 and 10 mΩ).

We observed positive upward leaders from the chimney using the high-speed video camera. During the observation, we obtained 15 video image files showing the propagation of an upward leader. Figure 1 shows high-speed video images of the inception and propagation of the positive upward leaders with the corresponding leader current. The current increases with the propagation of the upward leader. A positive upward leader current consists of only a continuous current immediately after the upward leader initiates from the chimney. The median value of the velocity of positive upward leaders was $5 \times 10^5$ m/s. We estimated the line charge density from the observation results. Immediately after the inception of the upward leader, the line charge density is about 0.2 mC/m. After that, the line charge density increases with the extension of the upward leader. At a leader length of 150 m, the line density is 1 mC/m.

We obtained data on the inception and propagation of a negative upward leader on 13th January 1991 using ALPS. Figure 2 shows ALPS images of the propagation of the negative upward leaders with the leader current waveform. A negative upward leader current consists of only current pulses without a continuous current component at the inception of the negative upward leader. The negative upward leader propagates intermittently similarity to a stepped leader. The time interval between the steps ranges from 2 to 46 µs with a mean value of 10 µs. The step length of the leader ranges from 13 to 135 m with a mean value of about 52 m.

The average velocity of the upward leader is $7.5 \times 10^5$ m/s. We estimated the line charge density from this result. At the inception of the upward leader, the line charge density is about 5 mC/m. Before the length of the upward leader reaches 400 m, the line charge density keep constant value of 5 mC/m. After the length of the leader exceeds 400 m, the line charge density starts to decrease.
Characteristics of Winter Lightning that Occurred on a Windmill and its Lightning Protection Tower in Japan

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Keywords: lightning, upward lightning, leader initiation

We have performed observation on several tens of lightning that hit on a windmill and its lightning-protection tower during the past 6 non-stop winter seasons from 2005 to 2010 at Uchinada-chou, Ishikawa prefecture of Japan. The windmill and the tower, with their heights of 100 m and 105 m, respectively, are separated at a distance of about 45 m and are built on a small hill just adjoining sea inlet. The hill’s height is about 40 m above the sea level.

Our main observation items are listed as follows,

1. Lightning current at the bottom of both the windmill and the tower by using Rogowski coils.
2. Continuous thunderstorm electric field by using field mills and the lightning electric field changes by using slow and fast capacitive antenna at multiple sites around the windmill with distances of several hundred meters to a few kilometers.
3. Ordinary video recordings and high speed images by using ALPS and high speed video camera several hundred meters from the windmill.

We have investigated the general lightning characteristics by analyzing the 36 lightning flashes for which we have recorded their electric currents. We found that positive, negative and bipolar lightning discharges make up roughly 11%, 64% and 25%, respectively, of the total 36 lightning flashes. Among the 4 positive lightning, 2 are downward lightning and 2 are upward lightning. All the negative and bipolar lightning discharges with a combined number of 32 are upward discharges. Considering that almost all the bipolar lightning (8 among 9) started with negative discharges, it is easy to note that more than 90% lightning on the windmill and its lightning protection tower were initiated by upward positive leaders.

All the 34 upward lightning did not contain return strokes, though majority of them have so called ICC pulses during their initial continuous current stages. A return stroke is supposed to occur when the current at the lower part of a discharge channel is cut off earlier than at upper channel sections. In Japanese winter thunderstorms, since their charge structures are usually low, our result may suggest that the current cut off scenario is not easy to take place in the case of low charge structures.

All upward lightning can be clearly classified into two types according to whether they are triggered by nearby lightning discharge activities or they are initiated without any preceding discharge activities as reported by us previously. We called the former other-triggered lightning and the latter self-initiated lightning. In this study, a total of 53 upward lightning have been identified and classified. Of them, 25 were self-initiated and the remaining 28 were triggered by other nearby lightning discharges.

Also we noted that different types of thunderstorms produced different percentages of self-initiated upward lightning. Usually more active thunderstorms with higher charge structures produce only other-triggered lightning. Based on these results, we speculate that summer thunderstorms, usually having a higher cloud base, may produce only other-triggered upward lightning from high grounded structures except that the structures are extremely high.

We have found evidence indicating that the wind and the windmill blade moving do have certain effect in assisting the initiation of an upward leader.

Figure 1 presents a comparison of the initial speed of upward lightning occurring at different observation sites of Nadachi and Uchinada.

![Fig. 1. Comparison of leader speeds for lightning occurring at different observation sites of Nadachi and Uchinada](image)

Based on the results observed in this study, we suggest the following practical rules for designing the lightning protection of high grounded structures to avoid direct lightning strikes.

1. Lightning rod should be installed at locations with potential strong wind and avoid emitting strong corona discharges.
2. On the contrary, at the locations to be protected it is better to actively produce corona discharges and to avoid strong wind.
3. If a high structure has some large horizontal objects high above the ground, besides vertical electric field, horizontal electric field component should also be taken into consideration to protect the objects from direct lightning strikes.
Electromagnetic Environment in the Vicinity of a Tall Tower Struck by Lightning—A Review—

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Keywords: lightning, return-stroke models, tall strike object, electromagnetic fields

The presence of an elevated strike object has been included in two classes of return-stroke models, namely the engineering models and the electromagnetic or Antenna-Theory (AT) models, as defined by Rakov and Uman (1).

In this paper, the author presents an overview of recent progress in the characterization of electromagnetic fields radiated by lightning strikes to tall structures.

First, models for lightning return strokes to tall towers are discussed. In all engineering models, the elevated strike object is modeled as an ideal transmission line (e.g., (2)). The adequacy of this assumption is discussed in the paper, making reference to experimental data and recent theoretical investigations (e.g., (3) (4)).

In contrast with electromagnetic models (5) for which electromagnetic fields are computed simultaneously with the distribution of the current along the radiating structure (strike object and lightning channel), the use of engineering models requires the evaluation of the associated electromagnetic fields. The calculation procedure essentially depends on the ground electromagnetic properties. Assuming the lightning channel as a lossless vertical antenna above a finitely conducting ground the associated electromagnetic fields can be evaluated using three different approaches: (1) use of dedicated algorithms; (2) use of simplified approaches; and (3) use of numerical methods such as the Method of Moments or the Finite-Difference Time-Domain (FDTD) technique (6).

The paper presents finally recent progress in the characterization of electromagnetic fields radiated by lightning to tall structures, making reference to experimental data obtained using different instrumented towers.

References

Performance of the Tohoku IMPACT Sensor Network in Winter Lightning Detection

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**Keywords:** lightning location, detection efficiency, winter

1. **Introduction**

A lightning location system (LLS) has been operated by Tohoku Electric Power Company, Inc. since 1994. This system consists of nine IMPACT sensors and detects lightning electromagnetic pulses (LEMPs) of magnitudes corresponding to peak currents from 10 to 300 kA within the observation area.

This system has been providing valuable information to the company to help it quickly identify transmission line (TL) faults caused by lightning. Lightning frequency statistics based on accumulated location data have been used to guide rational investment in electrical facility design for lightning tolerance. For lightning flashes causing the TL faults in winter, however, the detection efficiency (DE) has been lower than that of summer. Solving this problem has been a high priority. Although the support for IMPACT sensors has ended, the evaluated DE will still be important to use the accumulated location data.

To investigate the cause of the lower DE of the Tohoku LLS in winter, observations of LEMPs in the region were conducted using a fast antenna (FA) network in the winter seasons from 2002 to 2004. Analyzing the observed LEMPs associated with lightning flashes causing the TL faults, most of the waveforms were different from those commonly observed in summer, as observed in other coastal areas of the Sea of Japan.

2. **Results**

The detection efficiency related to the TL faults was 62% for lightning flashes (Table 1), but decreased to 56% for the first lightning strokes (Table 2). Classifying the first lightning strokes by discharge types, the detection efficiencies were 95% for negative cloud-to-ground (−CG) strokes, 23% for negative ground-to-cloud (−GC) strokes, and 67% for +GC strokes. GC strokes accounted for 73% of the entire group of investigated strokes, and rejected GC strokes also accounted for 95% of all rejected strokes.

In analyzing the LEMP waveforms, it was found that the rejections were caused by an incompatibility of the features of the LEMP waveforms with the waveform discrimination criteria as shown in Table 3, and the influence of the field pulses prior to the main pulse on the signal processing in the IMPACT sensor. The initial field change duration, measured in 67 strokes, was also found to be useful as a CG/GC classifier of both polarities as shown in Fig. 1.

**Table 1. Detection quantity and efficiency of the Tohoku LLS for lightning flashes causing TL faults in each investigated winter**

<table>
<thead>
<tr>
<th>Year</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>Total</th>
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<tbody>
<tr>
<td>Total number</td>
<td>29</td>
<td>38</td>
<td>28</td>
<td>95</td>
</tr>
<tr>
<td>Detected number</td>
<td>20</td>
<td>23</td>
<td>16</td>
<td>59</td>
</tr>
<tr>
<td>Rejected number</td>
<td>9</td>
<td>15</td>
<td>12</td>
<td>36</td>
</tr>
<tr>
<td>DE [%]</td>
<td>69</td>
<td>61</td>
<td>57</td>
<td>62</td>
</tr>
</tbody>
</table>

**Table 2. Detection quantity and efficiency of the Tohoku LLS for the first lightning strokes causing TL faults for each of the CG/GC strokes polarities in the same period as Table 1**

<table>
<thead>
<tr>
<th>Discharge type</th>
<th>−CG</th>
<th>−GC</th>
<th>+CG</th>
<th>+GC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>22</td>
<td>39</td>
<td>4</td>
<td>30</td>
<td>95</td>
</tr>
<tr>
<td>Percentage [%]</td>
<td>23</td>
<td>41</td>
<td>4</td>
<td>32</td>
<td>100</td>
</tr>
<tr>
<td>Detected number</td>
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<td>9</td>
<td>3</td>
<td>20</td>
<td>53</td>
</tr>
<tr>
<td>Rejected number</td>
<td>1</td>
<td>30</td>
<td>1</td>
<td>10</td>
<td>42</td>
</tr>
<tr>
<td>DE [%]</td>
<td>95</td>
<td>23</td>
<td>75</td>
<td>67</td>
<td>56</td>
</tr>
</tbody>
</table>

**Table 3. Quantities and rates of rejected lightning strokes summarized in Table 2 for the field waveform discrimination criteria of the IMPACT sensor**

<table>
<thead>
<tr>
<th>Field waveform discrimination criteria</th>
<th>−CG</th>
<th>−GC</th>
<th>+CG</th>
<th>+GC</th>
<th>Total</th>
</tr>
</thead>
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<tr>
<td>Rise time (Tr1) &gt; 30 [μs]</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>Percentage [%]</td>
<td>0</td>
<td>13</td>
<td>0</td>
<td>43</td>
<td>18</td>
</tr>
<tr>
<td>Zero-crossing time (Tz) &lt; 6 μs</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Percentage [%]</td>
<td>5</td>
<td>10</td>
<td>0</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Bipolar ratio (Ip) &gt; 1.0</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Percentage [%]</td>
<td>0</td>
<td>18</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Pre-trigger-δibosh (PTK) &gt; 0.25</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Percentage [%]</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total Number</td>
<td>22</td>
<td>39</td>
<td>4</td>
<td>28</td>
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</tbody>
</table>

**Fig. 1.** Histograms of initial field change duration (Ti) prior to the main pulse associated with the first lightning strokes in (a) negative polarities and (b) positive polarities. Bins along the right edges are out of range.
An Identification Method of Magnetizing Inrush Current Phenomena by Voltage Waveform

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Keywords: voltage waveform, magnetizing inrush current, voltage dip, distribution system, power quality, Aitken's Δ²-process

In medium voltage distribution systems, there are many power quality troubles due to voltage dips. Otherwise, a magnetizing inrush current causes the voltage dip. To suppress voltage dips, it is necessary to identify the magnetizing inrush current phenomena.

An identification condition is that the flux at saturation on time \(T_s\) is equal to the flux at saturation off time \(T_e\). The Eq. (1) shows a condition.

\[
\Phi(T_e) - \Phi(T_s) = \int_{T_s}^{T_e} v(\tau)d\tau = 0 \quad \cdots \cdots \cdots \cdots \cdots (1)
\]

where, \(v(t)\): voltage, \(\tau\): dummy variable.

In Eq. (1), since the minimum saturate flux and residual flux are not explicit, the magnetic characteristics are not needed. In this method, it is very important to estimate \(T_s/T_e\).

In this paper, the authors propose a new identification method of the magnetizing inrush current phenomena. In general, the identification is done using with current waveform. However, the saturation of CT (current transformer) can’t give waveform. Figure 1 shows current, voltage and flux at saturation. Therefore, the authors introduce the identification method using with voltage waveform, in which the saturation of VT (voltage transformer) doesn’t happen.

And then, to estimate the \(T_s/T_e\), the Aitken’s Δ²-process is adopted to voltage waveform. In this method, the index \(\delta V_{\text{min}}\) of estimating condition is introduced and is defined as follow

\[
\delta V_{\text{min}} = \min_n (|\delta V_n|) \quad \cdots \cdots \cdots \cdots \cdots (2)
\]

where, the suffix \(n\) is time step and \(\delta V_n\) is a variation voltage.

\[
\delta V_n = \frac{(V_n - V_{n+1}^2)}{V_n - 2V_{n+1} + V_{n+2}} \quad \cdots \cdots \cdots \cdots \cdots (3)
\]

Figure 2 shows that the index \(\delta V_{\text{min}}\) becomes minimum at \(t = T_s\), but not at \(t = T_e\). Therefore, to estimate \(T_s\), the new index \(\delta V_{\text{min}}'\) is introduced in which use the derivative voltage \(V'\) instead of \(V\).

The estimation steps of \(T_s/T_e\) are as follows:

Step 1; Using \(\delta V_{\text{min}}\), \(T_s\) and \(\Phi(T_s)\) are estimated.

Step 2; From the condition \(\Phi(t) = \Phi(T_s)\), a virtual off time \(t = T_e'\) is assumed.

Step 3; The most near time to \(T_e'\) in all \(\delta V_{\text{min}}'\) becomes \(T_e\).

Figure 3 shows the steps of the estimation.

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Fig. 1. Waveforms at CT saturation

Fig. 2. Estimation of \(T_s, T_e\)

Fig. 3. Case of CT saturation
An Estimation Method to Determine Equivalent Circuit Parameters for the Harmonic Analysis

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Keywords: harmonic analysis, equivalent circuit, parameters estimation, ATP-EMTP, harmonic characteristics curve

This paper proposes a new estimation method to determine any circuit parameters for the harmonic analysis of distribution network of power system. The harmonic analysis is very important to maintain quality of electric power. An interesting phenomenon, which is the cut-down of harmonic voltage level temporarily at dawn even if demand is a little bit increasing at this time, is often observed in the actual power system. Figure 1 shows an example monitoring results at one of distribution substation bank, named KE1B, at 21th February 2011.

This paper proposes utilizing the observation results of this phenomenon to estimate circuit parameters. In addition, this paper claim that detail equivalent circuit is more preferable for explaining that phenomenon than conventional simplified equivalent circuit. This paper also discusses the usefulness of the Harmonics Characteristics Curve, which is the proposed by this paper as new concept, at secondary winding of distribution transformer and the correlation of PQ, which are monitored values of active and reactive power at secondary winding of distribution transformer. This correlation should determine the equivalent fundamental harmonic admittance of among of the shunt capacitors installed concerning distribution lines.

Figure 2 shows the comparison the results from equivalent circuit calculation using estimated circuit parameters and the monitoring values on concept of the harmonic characteristics curves. It is possible to evaluate that estimated values are enough accurate practically, because monitoring data are well fitted on the curve from the analysis based on equivalent circuit with estimated parameters.

Fig. 1. Monitoring Results at Secondary winding of KE1B

Fig. 2. Analysis Results at Secondary Winding of KE1B
A TLM-based Surge Analysis of Grounding Electrodes

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Keywords: transmission line modeling (TLM) method, finite difference time domain (FDTD) method, electromagnetic field, surge

In this paper, representations of a perfectly conducting thin wire and an imperfectly conducting medium in the transmission-line-modeling (TLM) calculation are briefly explained. Then, the TLM method is applied to analyzing surge responses of a vertical parallelepiped grounding electrode and a square-loop grounding electrode.

Figure 1 shows the configuration, which represents the experimental setup employed by Tanabe et al. for evaluating the surge response of a vertical parallelepiped grounding electrode. The electrode length is 3 m, and has a square cross-section of $0.5 \times 0.5$ m. The conductivity of ground is set to 2.28 mS/m, and its relative permittivity is set to 50.

Figure 2(a) shows the TLM-calculated waveform of current, which is injected in the top of the 3-m long vertical grounding electrode, and corresponding FDTD-calculated and measured waveforms. Figure 2(b) shows those of voltage at the top of the vertical grounding electrode. It follows from Fig. 2 that TLM-calculated surge waveforms for the vertical grounding electrode agree well with the corresponding FDTD-calculated and measured waveforms. Also, TLM-calculated waveforms of surge current and voltage for a square-loop electrode, which are not shown in this extended summary but shown in the paper, agree reasonably well with corresponding measured waveforms.

Fig. 1. Configuration for testing the surge response of a vertical parallelepiped grounding electrode

Fig. 2. TLM- and FDTD-calculated waveforms of current and voltage at the top of the vertical parallelepiped grounding electrode, and the corresponding waveforms measured by Tanabe et al.

It is probably the first time that surge responses of a conductor system including a lossy ground and grounding electrodes are analyzed reasonably accurately using the TLM method, although the TLM method is presently inferior to the FDTD method in terms of computation time and memory required. This is a prospective step forward to the practical use of the TLM method in surge analyses.