Frequency Spectrum Analysis of Electromagnetic Waves Radiated by Electric Discharges

Dae-Won Park*, Gyung-Suk Kil†, Sang-Gyu Cheon**, Sun-Jae Kim** and Hyeon-Kyu Cha***

Abstract – In this paper, we analyzed the frequency spectrum of the electromagnetic waves radiated by an electric discharge as a basic study to develop an on-line diagnostic technique for power equipment installed inside closed-switchboards. In order to simulate local and series arc discharges caused by an electric field concentration and poor connections, three types of electrode systems were fabricated, consisting of needle and plane electrodes and an arc generator meeting the specifications of UL 1699. The experiment was carried out in an electromagnetic anechoic chamber, and the measurement system consisted of a PD free transformer, a loop antenna with a frequency bandwidth of 150 kHz–30 MHz, an ultra log periodic antenna with a frequency bandwidth of 30 MHz–2 GHz, and an EMI test receiver with a frequency bandwidth of 3 Hz–3 GHz. According to the experimental results, the frequency spectra of the electrical discharges were widely distributed across a range of 150 kHz–400 MHz, depending on the defects, while commonly found between 150 kHz and 10 MHz. Therefore, considering the ambient noise and antenna characteristics, the best frequency bandwidth for a measurement system to monitor abnormal conditions by detecting electromagnetic waves in closed-switchboards is 150 kHz–10 MHz.

Keywords: Electromagnetic wave, Series arc discharge, Corona discharge, Frequency spectrum, Closed-switchboard

1. Introduction

Researches on diagnostic techniques for power equipment have long been actively conducted to achieve highly stable power supplies. The major causes of faults in power equipment are insulation breakdown and poor connections [1-3]. These are caused by electrical, thermal, and chemical stresses and are closely related to the performance and lifetime of the equipment [4, 5]. Fig. 1 shows the statistics for electrical faults in power equipment in Korea. For indoor power equipment, the accident rate was the highest in closed-switchboards (45%), with more than 50% of these accidents caused by electric discharges as the result of insulation deterioration and poor connections, which create local and series arc discharges [6]. Therefore, this paper analyzed the frequency spectrum of the electromagnetic waves generated by local and series arc discharges to develop an on-line diagnostic technique for the power equipment installed in closed-switchboards [7]. Closed-switchboards are electrically grounded metallic enclosures with transformers, circuit-breakers, and control devices installed inside. The electromagnetic waves generated by these pieces of equipment are not propagated outward but are shielded or attenuated by the enclosure. In addition, electromagnetic waves from the outside cannot propagate into the switchboard. Therefore, the detection of electromagnetic waves can be used to monitor the condition of closed-switchboards.

2. Theory

2.1 Local discharge

When the electric field is concentrated because of insulation deterioration or structural defects, a local
discharge accompanied by light and sound occurs and radiates electromagnetic waves. As shown in Fig. 2(a), surface discharge is generated by a lack of creepage distance resulting from an improper insulation design or a decrease in creepage distance from the presence of a foreign substance on the surface of the insulation materials. If surface discharge continues over a long period, erosion or corrosion occurs on the surface of the insulation materials, which reduces the performance and can form a carbonized path, resulting in insulation breakdown.

Corona discharge is a type of local discharge generated when an electric field is concentrated around a sharp point on a conductor. It has a current of a few μA, as well as polarity effects [8]. Likewise, if a corona discharge continues in electrical equipment, it decreases the dielectric strength and causes insulation breakdown. Because a local discharge occurring in a void inside an insulation material is extremely low, it is not possible to detect it through the condition monitoring of closed-switchboards.

2.2 Series arc discharge

An arc discharge is a phenomenon that consecutively radiates intense flashes of light. Arc discharges can be divided into series and parallel types depending on the generation mechanism [9, 10].

As shown in Fig. 3, a series arc occurs at an electrical junction in series with a load and is caused by an incomplete connection as the result of corrosion or vibration. The current flowing is much less than that of a parallel arc, but can causes line-to-ground faults or short circuits by oxidizing and thermally degrading the surrounding insulation materials [11-14].

3. Experiment and Method

In order to measure the radiated electromagnetic waves generated by electric discharges in power equipment inside closed-switchboards in wide ranges, the experiment system consisted of a PD free transformer, a loop antenna with a range of 150 kHz–30 MHz, an ultra log periodic antenna with a range of 30 MHz–2 GHz, and an EMI test receiver with a range of 3 Hz–3 GHz. The antenna was fixed vertically 1 m from the ground, and the distance between the antenna and electrode system was 3 m since the discharge current in electrode systems flows in vertical direction.

As shown in Fig. 4, all of the measurements were conducted in a 15 m×28 m×10 m electromagnetic anechoic chamber to create an environment similar to a closed-switchboard. Under the above mentioned experimental conditions, the measurement level was set by analyzing the antenna characteristics and background noises.

To simulate local discharges by electrical field concentrations in power equipment, three types of electrodes systems were fabricated: a needle-plane with pressboard, plane-plane with pressboard, and needle-plane with air gap, as shown in Fig. 5 [15, 16].
In addition, the electrode system was connected in series to a 10 MΩ resistor to maintain the discharges by limiting the current. A surface discharge was generated by maintaining a 1.6 mm distance between the electrodes by inserting a pressboard between them, as shown in Fig. 5(a) and Fig. 5(b). The plane electrode was made of a tungsten-copper alloy disc to avoid electric field concentration, and the discharge at the needle electrode was induced by minimizing the radius of the needle electrode's curvature.

In the configuration shown in Fig. 5(c), the distance between the electrodes was 5 mm and no pressboard was inserted between them, allowing a corona discharge to be generated at a relatively low voltage. All the electrode systems were fixed vertically to flow discharge current in vertical direction.

An arc generator specified in UL1699 as shown Fig. 6 was used to produce series arc and was installed vertically [17].

4. Results and Discussion

The background noise in the electromagnetic anechoic chamber is shown in Fig. 7. The background noise was 24–32 dBμV/m in the loop antenna range of 150 kHz to 30 MHz, with characteristics equal to those of the loop antenna. The electric field strength had minimum and maximum values of -10 dBμV/m and 40 dBμV/m, respectively, when measured at the frequency bandwidth of the ultra log periodic antenna (30 MHz–2 GHz).

We confirmed that no extraneous electromagnetic waves occurred in the experimental system installed in the electromagnetic anechoic chamber, and analyzed the radiated electromagnetic waves upon local and series arc discharges on the basis of the background noise.

4.1 Local discharge

A commercial frequency high voltage was applied to each electrode system, and the frequency spectrum of the
emagnetic waves measured upon local discharge is shown in Fig. 8. As shown in Fig. 8, the frequency spectrum of the radiated electromagnetic waves upon surface discharge in the needle-plane electrode system was distributed intermittently at 500 kHz–600 kHz, 1.6 MHz–2.6 MHz, 5 MHz–30 MHz, and 30 MHz–500 MHz.

Fig. 8. Frequency spectrum for a needle-plane electrode of Fig. 5(a).

Fig. 9 shows the frequency spectrum of the radiated electromagnetic waves in the plane-plane electrode system. Unlike the needle-plane electrode system, it shows a continuous distribution in the 150 kHz–150 MHz range.

Fig. 10 shows the frequency spectrum of the radiated electromagnetic waves upon corona discharge in the needle-plane electrode system. Just as with the surface discharge in the needle-plane electrode system, it is distributed intermittently at 300 kHz–400 kHz, 600 kHz–30 MHz, and 30 MHz–350 MHz.

Table 1 shows the characteristic frequency bands of the abovementioned frequency spectra based on values of 40 dBμV/m and greater, considering the antenna characteristics and background noises.

Considering the characteristic of a closed-switchboard that the frequency generated at each electrode system can be distinguished from the background noise in discharge detection, along with the frequency characteristics of the detection systems, electromagnetic waves should be detected from the frequency bands shown in Table 1.
Table 1. Frequency spectra in surface and corona discharges.

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Type</th>
<th>Loop antenna (150 kHz–30 MHz)</th>
<th>Ultra log periodic antenna (30 MHz–2 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Needle(0.2 mm)-Plane</td>
<td>500 kHz–600 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.6 MHz–2.6 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 MHz–30 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plane-Plane</td>
<td>150 kHz–30 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>30 MHz–32 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Needle(10 μm)-Plane</td>
<td>300 kHz–400 kHz</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>600 kHz–30 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 MHz–30 MHz</td>
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</table>

4.2 Series arc discharge

Fig. 11 shows the frequency spectrum when the series arc generated at a carbon rod-copper electrode was distributed intermittently at 150 kHz–1 MHz and 30 MHz–600 MHz.

As shown in Fig. 12, the electromagnetic waves radiated by the series arc generated by the poor contacts on the terminal block were distributed at 150 kHz–9 MHz and 30 MHz–800 MHz.

The characteristic frequency spectra are shown in Table 2, considering the characteristics of the antenna and the background noise based on values of 40 dBμV/m and greater.

In summary, the frequencies of the electromagnetic waves radiated upon local and series arc discharges, as shown in Tables 1 and 2, respectively, were widely distributed across a range of 150 kHz–400 MHz, but had common frequency bands distributed across a range of 150 kHz–10 MHz.

Fig. 13 shows a summary of the frequency distributions of the electromagnetic waves radiated upon local and series arc discharges. The radiated electromagnetic waves were distributed across a range of 150 kHz–400 MHz. However, all of the radiated electromagnetic waves from the electrode systems used in the experiment had the 150 kHz–10 MHz range in common.

Table 2. Frequency spectra in series arc discharge.

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Type</th>
<th>Loop antenna (150 kHz–30 MHz)</th>
<th>Ultra log periodic antenna (30 MHz–2 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon rod-copper electrode</td>
<td>150 kHz–400 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terminal block</td>
<td>150 kHz–9 MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 11. Frequency spectrum for the carbon rod-copper electrodes.

Fig. 12. Frequency spectrum for the terminal block.

Fig. 13. Frequency spectrum of electric discharge.
Therefore, a frequency band of 150 kHz–10 MHz is suitable for the monitoring of abnormal conditions by detecting electromagnetic waves in closed-switchboards.

5. Conclusion

This study conducted a basic investigation to develop an on-line diagnostic technique for the power equipment mounted in closed-switchboards. We analyzed the frequency spectrum of the electromagnetic waves generated by local discharges as the result of electric field concentrations and series arc discharges from poor contacts, which cause more than 50% of the accidents in closed-switchboards. Experiments were conducted in an electromagnetic anechoic chamber to simulate an environment similar to a closed-switchboard, which is shielded from external electromagnetic waves. The measurement range was 150 kHz–2 GHz, and two measurement systems were used simultaneously: a loop antenna with a range of 150 kHz–30 MHz and an ultra log periodic antenna with a range of 30 MHz–2 GHz. The frequency spectra of local and series arc discharges were widely distributed across a range of 150 kHz–400 MHz with various defects, but they had a common frequency band of 150 kHz–10 MHz.

In conclusion, considering the antenna characteristics and background noise, a frequency spectrum of 150 kHz–10 MHz is suitable for diagnosing abnormal conditions by detecting radiated electromagnetic waves in closed-switchboards.

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