A Study on the Electrical Characteristics of ZnO Blocks
by a Multiple-lightning Impulse Current
- II -
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A Study on the Electrical Characteristics of ZnO Blocks by a Multiple-lightning Impulse Current

by Lee, Jong-Hyuk

Department of Electrical Engineering
The Graduate School of Korea Maritime University
Pusan, Republic of Korea

Abstract

This thesis deals with the changes of the electrical characteristics of ZnO blocks by the application of a single and a multiple-lightning impulse current.

Lightning arresters are the best protective device on electrical power systems against transient overvoltages caused by lightning impulse current and switching operation. Until these days, lightning arresters are estimated only by a single-lightning impulse current in its performance test. However, a multiple-lightning impulse currents are a general feature of natural lightning-ground flashes. It is therefore necessary for lightning arresters to be estimated by applying
not only a single-lightning impulse current but also a multiple-lightning impulse current.

In this study, ZnO blocks of 6 [kV], 5 [kA] used in power distribution system have been estimated repeatedly until 200 times by a single and a multiple-lightning impulse current of 8/20 [us], 5 [kA].

The multiple-lightning impulse current generator which can produce quadruple 8/20 [us], 5 [kA] with discrete time between 30~120 [ms] is designed and fabricated. The total energy applied to the ZnO blocks at each pulse is about 1,200 [J].

In experiment, various parameters such as leakage current components, reference voltage, and surface temperature of ZnO blocks are measured with the number of applied impulse current. Also, micro-structure changes of ZnO blocks after applying the single and the multiple-lightning impulse current of 200 times are compared.

From the experimental results, the peak value of the leakage current and the surface temperature of ZnO blocks are increased continuously with the number of applied impulse current, but no significant changes in the RMS value of the leakage current and in the reference voltage are observed.

Also, it is confirmed that the type of ZnO blocks are more vulnerable in deterioration or damage to the multiple-lightning impulse current.
1

A lightning arrester (Lightning Arrester) is a device that is designed to protect electrical equipment from damage caused by lightning. Lightning-arrester (Lightning Arrester) devices have been used since the early 20th century. The first lightning-arrester was developed in 1930 and was made of silicon carbide (SiC). SiC is a semiconducting material that is able to withstand high electrical currents. In 1970, ZnO lightning-arrester (ZnO) devices were developed. ZnO is a high breakdown voltage material that is able to withstand high electrical currents.

In 1980, follow current (air gap) lightning-arrester devices were developed. Follow current (air gap) lightning-arrester devices are able to withstand high electrical currents and are used in applications where high electrical currents are expected.
ZnO  and  SiC.  

\[ \text{ZnO} \]  

\[ \text{SiC} \]
Table 1. Statistical reports on major failure causes in power distribution lines

<table>
<thead>
<tr>
<th></th>
<th>RS</th>
<th>G/S</th>
<th>R/C</th>
<th>I/S</th>
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<td>17(22)</td>
<td>19(43)</td>
<td>0(11)</td>
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<td>5(4)</td>
<td>83(130)</td>
<td>6</td>
<td>26</td>
<td>20</td>
</tr>
<tr>
<td>RS</td>
<td>6</td>
<td>26</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>34</td>
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<tr>
<td>G/S</td>
<td>9</td>
<td>14</td>
<td>4</td>
<td>1</td>
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<td>1</td>
<td>30</td>
<td>9</td>
<td>14</td>
<td>4</td>
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<tr>
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<td>4</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>19</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>I/S</td>
<td>62</td>
<td>49</td>
<td>37</td>
<td>3</td>
<td>0</td>
<td>8</td>
<td>159</td>
<td>62</td>
<td>49</td>
<td>37</td>
</tr>
<tr>
<td>(%)</td>
<td>36.6</td>
<td>33.0</td>
<td>20.1</td>
<td>4.5</td>
<td>1.6</td>
<td>4.2</td>
<td>100</td>
<td>36.6</td>
<td>33.0</td>
<td>20.1</td>
</tr>
</tbody>
</table>

* 1. 99% ±â Ÿ 62.6% ±â Ÿ (32% ±â Ÿ), 32.1% ±â Ÿ 36.6% ±â Ÿ

2. ( ) ±â Ÿ 98% ±â Ÿ
Fig. 1.1 Comparison of the standards for lightning arrester test
Fig. 1.2 Growth progress of a return stroke
Fig. 13  Progress of lightning discharge

1.3

ZnO
ZnO 赤血鉄の生成に
関与する可能性が示唆されている。

2.1 ZnO

zinc, bismuth, cadmium, boron, aluminum, antimony, cobalt, manganese, barium, titanium, silicon

ZnO ppm range is 95 ~ 97%. The ZnO crystal size is 10 ~ 20 nm. The (spinel) ZnO grain boundary is 100 Å. The Bi₂O₃ ZnO grain size is also mentioned. [20]–[23]
Fig. 2.1 Structure of a ZnO block
\[ V_b = n v_b \quad [V] \quad \text{(2.1)} \]

\[ V_b = \text{ZnO} \quad \text{[V]} \]
\[ n = \text{[V]} \]
\[ v_b = \text{[V]} \]

\[ \text{ZnO} \quad \text{[V]} \]

From eq. 2.1 (a), the band gap 3 \sim 4 [V].
Fig. 2.2 Micro-structure of a ZnO block

2.2 ZnO 

ZnO block (SEM)

10 µm

grain boundary

pore

ZnO

grain

(15k x 1,000)

ZnO

pore

(depletion layer)
(ionized defects) \[2.3\]

(double schottky barrier) bias \[2.4\]

Fig. 2.3 Energy-band model of a ZnO block

2.3 ZnO

2.4

2.5 (Prebreakdown region) ZnO

2.6 (Upturn region) ZnO
Fig. 2.4 E-J characteristics of a ZnO block

\[ J = kE^\alpha \quad \text{[A/cm²]} \]  \hspace{2cm} (2.2)

\[ J = \text{ZnO} \]  \hspace{2cm} \[ E = \text{ZnO} \]
\[ k = \text{---} \]
\[ \alpha = \text{---} \]

\[
\begin{align*}
\text{ZnO} & \quad \text{ZnO} \\
R_s & \quad R_s \quad \text{ZnO} \\
C_r & \quad \text{ZnO} \\
\end{align*}
\]

Fig. 2.5 Electrical equivalent circuit of a ZnO block
Fig. 2.6 Example of a leakage current waveform

2.2 Example of a leakage current waveform

ZnO の特性を示す波形の一例を図 2.6 に示す。ZnO の特性は、主に電圧、温度、湿度などによって影響を受け、これらの条件が変化するごとに波形も変化する。したがって、ZnO の特性を把握するために、これらの条件を精度よく制御することが重要である。
\[ I_r = A \exp \left( - \frac{Q}{K T} \right) \]  

[A]  

(2.3)
Fig. 2.7 Photograph of the damaged ZnO block

ZnO block is shown in Fig. 2.7 (a) and (b). The photograph shows the damage on the surface of the ZnO block. ZnO is a semiconducting material, and its electrical properties can be measured using a (pin-hall) method. The results are shown in the figures.
陶磁器製造・加工・修復・保存技術について、さまざまな開発が行われています。特に、古くは陶磁器の表面に小さな欠陥や亀裂が生じることがありました。この問題を解決するため、新しい技術が導入されています。[5]

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3. ZnO の特性

ZnO の特性について、以下のようなことが示されています。

- 2. ZnO の特性

Table 2. Electrical characteristics of the ZnO block

<table>
<thead>
<tr>
<th></th>
<th>AC 7.2 ~ 8.64 [kV] rms (1mA)</th>
<th>DC 8.6 ~ 10.12 [kV] (1mA)</th>
</tr>
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<tbody>
<tr>
<td>6 [kV] rms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 [kA] rms</td>
<td></td>
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</table>

3.1 ZnO の特性 1

ZnO の特性について、さらに詳しく説明された内容が2.1節に示されています。

- ZnO の特性 2

特性 3.1 (100 [mm]) 8 [kV] (100 [kV]) 0.5 [mA]
3.1 Configuration of the experimental apparatus and measurement system

Fig. 3.1 Configuration of the experimental apparatus and measurement system

ZnO (Stangenes. CT 3-0.01, 50 [kA] max) ZnO 1000:1 (Tek. P6015A, 75 [MHz], 40 [kV] max)

3.2 ZnO HV PS DC/AC, 40 [kV] 5 [mA]) (R), (CT)
Fig. 3.2 Configuration of the measurement system for leakage currents

- R: 전류 제한용 저항
- ZnO: 피뢰기 소자
- HV PS: 고전압 인가전원 (AC, DC 40kV~5mA)
- CT: 관통형 고주파 변류기
- uA: 적류 전류지
- CD: 전자 누설전류 검출화로
Fig. 3.3 measurement circuit for leakage currents
Fig. 3.4 Equivalent circuit of a lightning impulse current generator

\[ L \frac{di}{dt} + (R_L + R_{OUT})i + \frac{1}{C} \int_0^t i \, dt = E \]  

(3.1)

\[ t = 0 \quad R_L + R_{OUT} = R \quad i \quad i = 0 \quad \]  

\[ R > 2\sqrt{\frac{L}{C}} \]

(3.2)

\[ i = \frac{E}{R} \cdot \frac{\alpha}{\beta} \{ e^{-i \alpha \beta t} - e^{-i \alpha \beta T} \} \]
2. \( R = 2\sqrt{\frac{L}{C}} \)

\[
i = \frac{E}{R} \cdot 2\alpha \cdot e^{-\alpha t}
\]  \hspace{1cm} (3.3)

3. \( R < 2\sqrt{\frac{L}{C}} \)

\[
i = \frac{E}{R} \cdot \frac{2\alpha}{\omega} \cdot e^{-\alpha t} \sin \omega t
\]  \hspace{1cm} (3.4)

\[
\alpha = \frac{R}{2L}, \quad \beta = \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}, \quad \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}
\]

3.5 (a)

3.5 (b)

3.5 (c)
Fig. 3.5 Impulse current waveforms
Fig. 3.6 Photograph of the multiple-lightning impulse current generator

70 [kV] 8/20 [\mu s], 5 [kA]
### Table 3. Specification of the multiple-lightning impulse current generator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>( R_s )</td>
<td>( t_r : 100 \text{[ns]} ) ( \text{Max} : 50 \text{[kA peak]} )</td>
</tr>
<tr>
<td>( G )</td>
<td>( 100 \text{[mm]} )</td>
</tr>
<tr>
<td>( R_o )</td>
<td>( 500 \text{[\mu F]} )</td>
</tr>
<tr>
<td>( L )</td>
<td>( 4 \sim 32 \text{[\mu H]} )</td>
</tr>
<tr>
<td>( C )</td>
<td>( 100 \text{[kV]}, 0.5 \text{[\mu A]} )</td>
</tr>
<tr>
<td>( R_L )</td>
<td>( 10 \text{[\Omega]} )</td>
</tr>
<tr>
<td>( H V D C )</td>
<td>( 130 \text{[kV]}, 2.1 \text{[mA]} )</td>
</tr>
</tbody>
</table>
Fig. 3.7  Typical waveforms produced by the multiple-lightning impulse current generator
3.3 \( \text{ZnO} \)

\[
E = \int v\,i\,dt \quad [W] 
\]

\[
v = \text{voltage} \\
i = \text{current} 
\]

\[
\text{ZnO} \quad 1200 [\text{J}] 
\]

\[
\text{ZnO} \quad 1200 [\text{J}] 
\]

\[
\text{ZnO} \quad 200 [\text{J}] 
\]

\[
\text{ZnO} \quad 50 [\text{J}] 
\]
(4.4 [kV]) and (6 [kV]) respectively. 1

ZnO coated samples were prepared by (glass coating) method and subjected to 4000 cycles of voltage at 100 Hz. The samples were characterized by SEM.

The SEM images for ZnO coated samples showed good adhesion of ZnO film onto the sample surface.
4.1 Changes of leakage current to A.C. applied voltage

Fig. 4.1 Changes of leakage current to A.C. applied voltage
Fig. 4.2 Changes of leakage current to D.C. applied voltage

\[ ZnO \quad 4.4 \text{ [kV]} \]
Fig. 4.3 Changes of leakage current to ambient temperatures
Fig. 4.4 Changes of reference voltages
ZnO

4.5 ZnO

40° (27 °C)
Fig 4.5 Changes of surface temperature of the ZnO blocks

ZnO \( (4.4 \text{kV}) \)
Fig. 4.6 Typical waveform of a leakage current
Fig. 4.7 Changes of leakage currents
A, B

\[ ZnO \]

\[ 2.1 (b) \]

\[ 4.7 (a) \]

\[ ZnO \]

\[ 200 \]

\[ 1/2 \]

\[ 8.33 \text{[ms]} \]

\[ ZnO \]
4.3 \textbf{結果}

ZnO の粉末を用いて、

\( 200 \) 倍の顕微鏡下での観察と

\( 40 \) 倍の顕微鏡下での観察を行いました。SEM による詳細な観察を行った。

4.8 (a) (b) において、ZnO の結晶構造を示し、

その詳細な観察を行いました。SEM による観察を示しています。
Fig. 4.8 Changes of a micro-structure of ZnO blocks

Fig. 4.8 (a) (b) (c)
ZnO について詳しく説明します。ZnO は、12.7 [J] [m] を示す。ZnO の熱伝導度は、13.6 [J] [m] [K] [s] [m] であり、他の元素に比べて優れていることが示されています。

ZnO の導電率は、4.7 (c) [S] [m] [K] [cm] であり、他の素材と比較すると高いです。ZnO の結晶構造は、4.8 (c) [Å] [m] [K] [cm] であり、他の材料に比べて安定しています。20 [Å] [m] [K] [cm] の結晶構造が、ZnO の特性を示しています。
1. ZnO
2. 1°
3. 2°

- 43 -
ZnO


[16] Andre Hamel, Guy St.-jean, “Comparison of ANSI, IEC and CSA standards’ durability requirements on station-type oxide surge...”


