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Electrical Behaviors of ZnO Elements under Combined Direct and Alternating Voltages

Soon-Man Yang*, **Bok-Hee Lee**† **and Seung-Kwon Paek****

Abstract – This paper presents the characteristics of leakage currents flowing through zinc oxide (ZnO) surge arrester elements under the combined direct-current (DC) and 60 Hz alternating-current (AC) voltages. The current-voltage characteristic curves (*I-V* curves) of the commercial ZnO surge arrester elements were obtained as a function of the voltage ratio α. At constant peak value of the combined DC and AC voltage, the resistive leakage current of the ZnO blocks was significantly increased as the voltage ratio α increased. The *I-V* curves under the combined DC and AC voltages were placed between the pure DC and AC characteristics, and the cross-over phenomenon in both the *I-V* curves and *R-V* curves was observed at the low current region. The ZnO power dissipation for DC voltages was less than that for AC voltage in the pre-breakdown region and reversed at higher voltages.

Keywords: ZnO element, Combined DC plus AC voltages, Leakage current, *I-V* characteristic, Crossover phenomenon, Surge protection

1. Introduction

High voltage direct current (HVDC) transmission systems are being used more and more because of the development of high voltage, high current silicon controlled rectifiers. The invention of effective DC air blast and SF_6 circuit breakers and ZnO lightning surge arresters also promoted the wide use of HVDC transmission lines. Today, there are over 40 HVDC lines throughout the world [1]. Basically, an HVDC transmission system consists of an AC-to-DC converter, a DC line, and a DC-to-AC converter. Many types of surge arresters can be employed in a converter station of HVDC transmission systems: phase-to-phase arresters, low-voltage DC winding arresters, valve arresters connected between anode and cathode, DC line arresters, bridge arresters, high-voltage DC winding arresters, DC bus arresters, smoothing reactor arresters, neutral line arresters, and AC bus arresters. Among them, DC bus arresters, neutral line arresters, and AC bus arresters are applied with pure DC and AC voltages, and the other types of arresters are applied with the combined DC and AC voltage [2].

In the pre-breakdown region, the resistive leakage current of the ZnO element under AC voltage is higher than that under the DC voltage. On the contrary, above the nominal conduction voltage, the DC resistive leakage current is much higher than the AC resistive leakage current. The electrical and physical properties of the ZnO element under DC, AC, and impulse voltages have been investigated intensively [3-7]. There is significant difference between DC and AC characteristics for a commercial ZnO element. The ZnO lightning arrester used in AC transmission and distribution systems are unsuitable as a lightning arrester for HVDC transmission systems, because HVDC transmission systems need surge arresters having excellent nonlinear characteristics and large energy absorption capability, which cannot be provided by surge arresters employed in AC transmission and distribution systems. Unfortunately, the data on the basic features and performance of ZnO lightning arrester elements under the combined DC and AC voltages existing in HVDC power systems are as yet insufficient, and further studies are required.

The aim of this study is to obtain useful data regarding the basic characteristics and performance of ZnO lightning arresters in HVDC transmission systems. The combined DC and AC voltage generator was specially designed and fabricated. The leakage current at voltages below and above the nominal conduction level was measured by using a ZnO element taken from commercial distribution lightning arresters. The leakage currents flowing through the ZnO element under the combined DC plus 60 Hz AC voltages were investigated. The *I-V* characteristic curves against applied voltage and voltage ratio are presented. The characteristic parameters of the equivalent resistance

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and power dissipation of the ZnO element were evaluated as a function of the magnitude and voltage ratio of the applied voltages.

2. Experimental

Characteristics of the leakage currents flowing through the ZnO element subjected to the combined DC and 60 Hz AC voltages were investigated. Fig. 1 shows the circuit diagram of the combined DC/AC voltage generator, which was specially designed for this work. The voltage generator can produce a peak voltage of 10 kV, and the magnitude and voltage ratio of the test voltage was easily controlled by adjusting the AC input voltage.

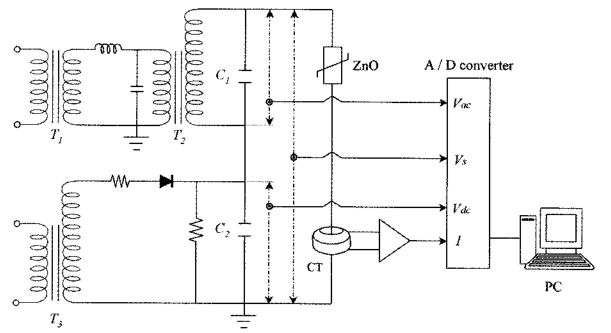


Fig. 1. Circuit diagram of the combined DC plus 60 Hz AC voltage generator.

The 60 Hz AC voltage is applied to capacitor C_1, and the DC voltage generated by a half-bridge rectifying circuit is applied to capacitor C_2. The low pass filter is employed between the transformers T_1 and T_2 to reduce noises in-flowed from the test circuit. If DC voltage is applied to capacitor C_2, the potential of the primary winding of transformer T_1 is varied with the transferred potential due to the stray capacitance between the primary and secondary windings of transformer T_2.

Generally, it is convenient to employ a parameter α to represent the voltage ratio of the peak (60 Hz) AC component of voltage V_{ac} to the peak of the combined voltage [8].

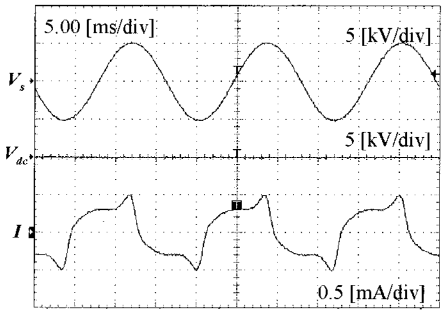
$$\alpha = \frac{V_{ac(peak)}}{V_{ac(peak)} + V_{dc}} \tag{1}$$

The ZnO element leakage current was detected by a sensitive current probe, and the test voltages were measured by the differential voltage active probes. When measuring the leakage current and voltages, these signals are sampled by a 12 bit A/D converter at a sampling rate of 10 Ms/s. The voltage and current signals are registered at a compatible personal computer. The test specimens used in this work were taken from the ZnO distribution lightning arresters with a rated voltage of 18 kV and a discharge current of 5 kA. The ZnO element is a column-type with a diameter of 33 mm and a height of 29 mm.

3. Results and Discussion

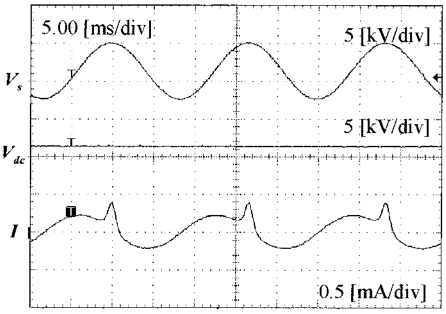
3.1 Oscillograms of the leakage currents

A series of experiments was carried out to measure and evaluate the characteristics of the leakage current flowing through a ZnO element. Fig. 2 shows oscillograms of the ZnO leakage current waveforms observed under the combined DC plus AC voltage of 5.2 kV peak, for various voltage ratios. The total leakage currents flowing through the ZnO element under the combined DC plus AC voltage are composed of the capacitive current and the resistive current. The leakage current under pure AC voltage (α=1) is a symmetrical waveform with positive and negative polarities. At voltages below the nominal conduction, the leakage current is highly capacitive. The capacitive current peak at the constant voltage crest level increases as the voltage ratio increases.



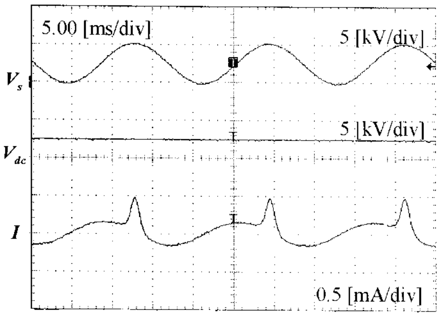
V_{ac} : 5.2 [kV$_p$], V_{dc} : 0 [kV], I_R : 0.5 [mA$_p$]

(a) α =1



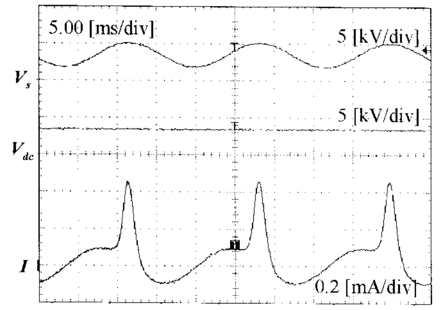
V_{ac} : 3.6 [kV$_p$], V_{dc} : 1.6 [kV], I_R : 0.4 [mA$_p$]

(b) α =0.7



V_{ac} : 2.6 [kV$_p$], V_{dc} : 2.6 [kV], I_R : 0.48 [mA$_p$]

(c) α=0.5



V_{ac} : 1.6 [kV$_p$], V_{dc} : 3.6 [kV], I_R : 0.44 [mA$_p$]

(d) α=0.3

Fig. 2. Waveforms of the applied voltage and leakage current of the ZnO element under the combined DC plus AC voltages of 5.2 kV peak, at various voltage ratios. V_s is the applied voltage, V_{dc} is the DC voltage, I is the leakage current.

The peak value of the resistive leakage current appears at the peak instant of the applied voltage. Under the combined DC plus AC voltage, the leakage current is asymmetric with positive and negative polarities.

The capacitive current decreases and the resistive leakage current increases with increasing the voltage ratio α. On the other hand, the ZnO leakage current waveforms under the combined DC plus AC voltage strongly depend on the voltage ratio α. At the pure AC test voltage of 5.2 kV peak and the voltage ratio α of unity, the peak value of capacitive current are lower than that of the resistive leakage current. For example, when the ZnO element is under the combined test voltage of 5.2kV peak, the peak value of the capacitive current at the voltage ratio of 0.5 is lower than that at the voltage ratio of unity, but the peak value of the resistive leakage current at the voltage ratio of 0.5 is higher than that at the voltage ratio of unity.

3.2 *I-V* characteristics

Generally, current is a more convenient, independent variable with devices such as ZnO elements that have an approximately constant voltage over a wide range of currents [9]. The *I-V* characteristics of the ZnO element were examined at a low leakage current of less than a few milliamperes. This region of the *I-V* characteristic is very important in the application of the ZnO element as it corresponds to the voltage stress under quiescent system conditions. The degradation of ZnO lightning arresters can be evaluated by using the resistive leakage current. Fig. 3 shows the *I-V* characteristic curves of the ZnO element as a function of the voltage ratio α of the combined DC and AC voltage in the low current region, at 20℃. Here, the *I-V* characteristic curves were plotted, showing the relationship between the peak values of the resistive leakage current and applied voltage. The reproduction of the voltage and current measurements in repeated tests were generally good, and the measurement errors were relatively small. The resistive current peak is not only voltage dependent but also voltage ratio dependent. The nominal conduction voltage V_{1mA}, at which the DC leakage current in the ZnO element is 1 mA, is approximately 5.25 kV.

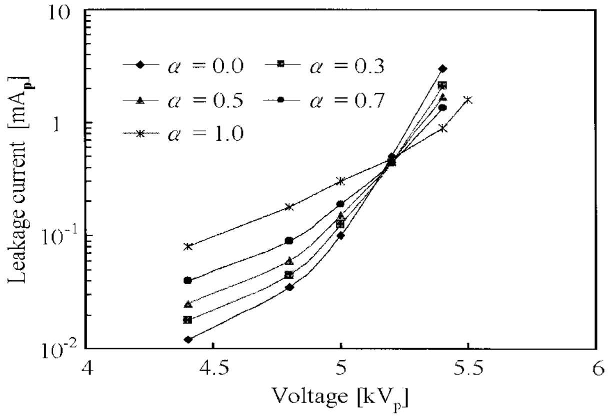


Fig. 3. *I-V* characteristic curves of the ZnO element under the combined DC and AC voltage

The electrical properties of the ZnO element can be characterized by an *RC* parallel circuit in the low conduction region. The leakage current at time *t* can be expressed as:

$$I(t) = C\frac{dV(t)}{dt} + I_R(t) \tag{2}$$

where $I_R(t)$ is the resistive leakage current, and C is the intrinsic capacitance of the ZnO element.

The peak value of resistive leakage current corresponds to the magnitude of the leakage current at the peak instant of applied voltage, because the capacitive current at the peak instant of applied voltage is zero. The *I-V* characteristics at the pure DC voltage (α=0) are different from those at the 60 Hz AC voltage. Below the leakage current of 0.5 mA peak, the *I-V* characteristic in

AC voltage is ohmic, but the *I-V* characteristic in DC voltage exhibits strong nonlinearity. This result suggests there are different leakage conduction mechanisms between DC and AC voltages at low voltage level. The leakage conduction at lower voltages is associated with thermal excitation over the depletion layer barrier.

The *I-V* characteristic curves in the combined DC and AC voltage are placed between the pure DC and AC voltages. The DC leakage current in the very low conduction is significantly smaller than the AC leakage current, but the DC leakage current exceeds the AC leakage current at higher voltages. That is, the *I-V* curves of the ZnO element under the pure DC and AC voltages cross over. Also, the crossover point of the *I-V* curves is approximately independent of the voltage ratio and magnitude of applied voltages.

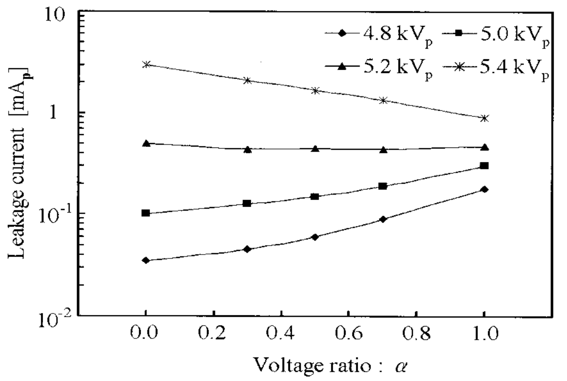


Fig. 4. Relationship between the leakage current and voltage ratio for the ZnO elements as a function of the peak value of applied voltage

The resistive leakage current against the voltage ratio α was plotted as a function of the magnitude of applied voltage in Fig. 4. The resistive leakage current is only slightly dependent on the voltage ratio at the 5.2 kV peak test voltage. The resistive leakage current in the current range of below the crossover point of the *I-V* curves increases as the voltage ratio increases. On the contrary, the resistive leakage current in current ranges above the crossover point of *I-V* curves decreases as the voltage ratio increases. The leakage current, below the nominal conduction current of 1 mA, increases as the voltage ratio increases. Unlike the low conduction rêgion, the resistive leakage current, at the voltage of 5.4 kV peak, shows a negative slope, which indicates a progressive transition of the ZnO element in both low and high conduction regimes from the AC to the DC characteristic when the voltage ratio α is varied from unity to zero [8]. At the early stage of breakdown region, the effect of the DC bias on conduction is more pronounced than that of AC voltage. In the pre-breakdown region, the current flow is caused by thermal excitation of the electron over the barrier, while in the breakdown region, the current flow is caused by the tunneling of the electrons through the barrier. As the Schottky barrier becomes thinner with increasing DC bias, electrical conduction is more likely to occur [10].

3.3 Equivalent resistance and power dissipation

(1) Equivalent resistance

The change in the resistance of ZnO elements represents the performance improvement or degradation of ZnO surge arresters, and this work analyzes the change of the equivalent resistance of ZnO elements. Fig. 5 shows the variations of the resistance against the magnitude of applied voltage, at several voltage ratios. The equivalent resistance in this paper is defined as the ratio of the peak value of applied voltage to the peak of the resistive component in the leakage current as expressed in equation (3).

$$R = \frac{V_{peak}}{I_{R(peak)}} \tag{3}$$

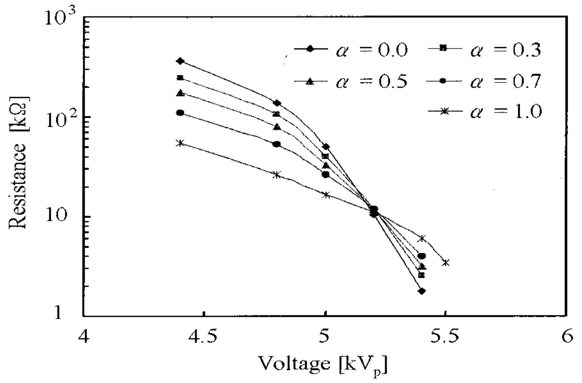


Fig. 5. Equivalent resistance of the ZnO element as a function of the amplitude of applied voltage

When the combined DC and AC voltage is applied across the ZnO element, the equivalent resistances are different from those measured under pure DC or AC voltage. The equivalent resistance of the ZnO element is strongly dependent on the peak value of applied voltage and the voltage ratio of applied voltages. The resistance of the ZnO element is inversely proportional to the magnitude of applied voltage. The resistance measured under pure DC voltages is much higher in the pre-breakdown region than that under the AC voltage or the combined DC and AC voltage. The nonlinearity of the resistance – voltage (*R-V*) characteristics under DC voltage (α=0) is more pronounced than that under AC voltage (α=1). The *R-V* curves in the combined DC and AC voltage ($0 < \alpha < 1$) are set between the DC and AC voltages.

Also, a lower voltage ratio α abruptly changes the equivalent resistance of the ZnO elements under the applied voltages. The crossover phenomenon was again observed in the *R-V* curves at the same applied voltage as it was in the *I-V* curves. The equivalent resistance of the ZnO element depends on the type and magnitude of the applied voltages. A crossover of the resistance versus applied voltage curves (*R-V* curves) under pure DC and AC voltage is revealed, as is that of the *I-V* characteristic curves. From the family of *R-V* curves, it is found that the crossover point of *R-V* curves was independent of the type of applied voltages and of the voltage ratio of the combined voltage.

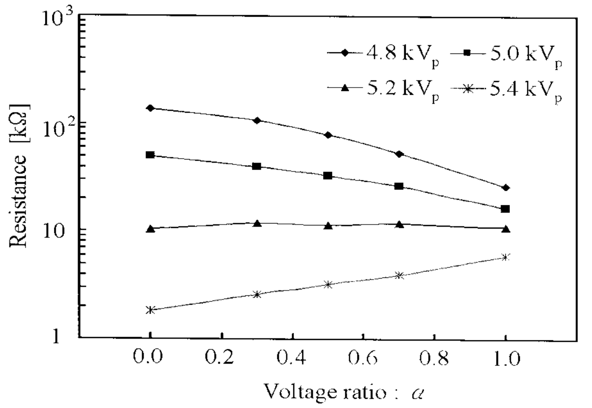
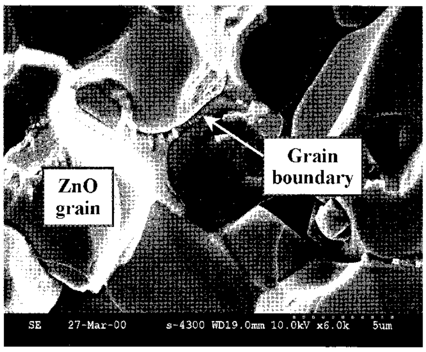


Fig. 6. Equivalent resistance against the voltage ratio as a function of applied voltage

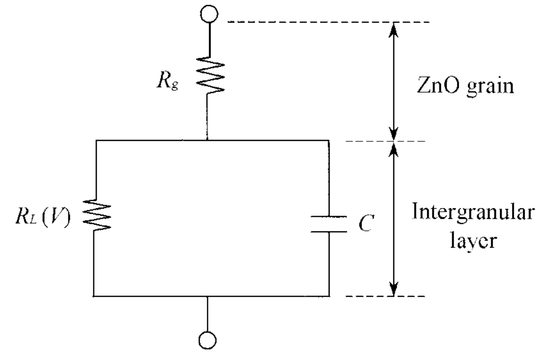
Once again, the equivalent resistance of ZnO elements is plotted as a function of the voltage ratio at various voltage peaks in Fig. 6. In the high conduction region, the equivalent resistance of the ZnO element increases in proportion to the voltage ratio. On the other hand, in the low conduction region, the resistance decreases as the voltage ratio increases. Generally, the resistance of the ZnO element is drastically decreased as the applied voltage increases, and the voltage dependence of the resistance against the voltage ratio at the DC voltage (α=0) is significantly greater than that at the AC voltage (α=1).

(2) Equivalent circuit

The conduction mechanism of ZnO elements seems to be quite different between DC and AC voltages. Generally, it is presumed that the leakage current flowing under DC voltage is due to the Schottky effect at the boundary layer between the ZnO grain and the intergranular layer [11]. The grain boundaries of ZnO elements are known to be very important in determining ZnO characteristics. The dielectric properties are basically caused by the thin depletion layers at the grain boundaries. The electrical characteristics of general ZnO elements depend directly upon the number of grain boundaries and the size of the ZnO grains.



(a) Microstructure



(b) Equivalent circuit

Fig. 7. Microstructure and equivalent circuit of the ZnO element used in this work

Fig. 7(a) shows the microstructure of the ZnO element used in this work. An equivalent circuit cannot represent some of the electrical characteristics of a ZnO element under all types of stresses. But, the equivalent circuit and experimental results could be summarized as follows: the ZnO grains will be characterized by a small resistance R_g and represent the characteristics of a large-scale current domain. Also, the intergranular layer is responsible for the nonlinear behaviors of the ZnO element. The intergranular layer at the grain boundaries is represented by the RC parallel circuit. The leakage resistance $R_L(V)$ is voltage-dependent and has highly nonlinear characteristics. The ZnO element has self-capacitance and parasitic capacitance to earth. But, the parasitic capacitance to earth is significantly small enough to be neglected. The self-capacitance C was voltage-independent in the pre-breakdown region. As a consequence, the simplified equivalent circuit of the ZnO element consisted of a small resistance R_g, representing the ZnO grains, in series with the RC parallel circuit as shown in Fig. 7(b).

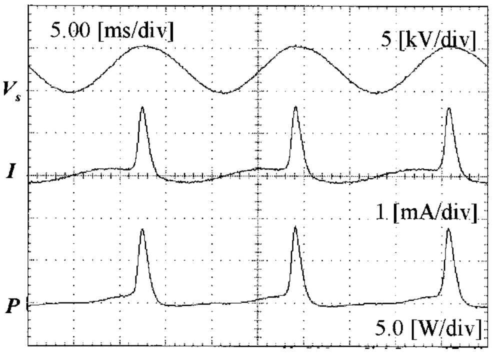
(3) Power dissipation

Power dissipation is a factor that can represent the electrical behaviors of a ZnO element and is closely related to the performance degradation of the ZnO element. Power dissipation was calculated from the average of the integration of the product of the applied voltage across the ZnO element and the leakage current through the ZnO element for a period, as given in equation (4).

$$P_{av} = \frac{1}{T}\int_0^T (V \times I)dt \qquad (4)$$

where V is the applied voltage, and I is the leakage current.

Also, the average power is computed by the numerical integration using the software of the digital storage oscilloscope with a microcomputer. Fig. 8 shows typical oscillographic waveforms of the power, applied voltage, and leakage current flowing through the test ZnO element under the combined DC and AC voltage of 5.4 kV peak, at the voltage ratio α of 0.5.



V_{ac}: 2.7 [kV$_p$], I_R: 1.68 [mA$_p$] P: 0.79 [W]

(c) V_s=5.4 [kV]

Fig. 8. Waveforms of the applied voltage, leakage current and power. The voltage ratio α'is 0.5, the applied voltage V_s is 5.4 kV peak, I is the leakage current, and P is the average power.

The change in the average power dissipation is plotted against the voltage ratio α for various peak voltages. Fig. 9 illustrates the family of the average power versus the voltage ratio characteristic curves for different magnitudes of applied voltages. Power dissipation increases as the applied voltage increases at a certain voltage ratio, and the variation is the maximum under DC voltage ($\alpha = 0$).

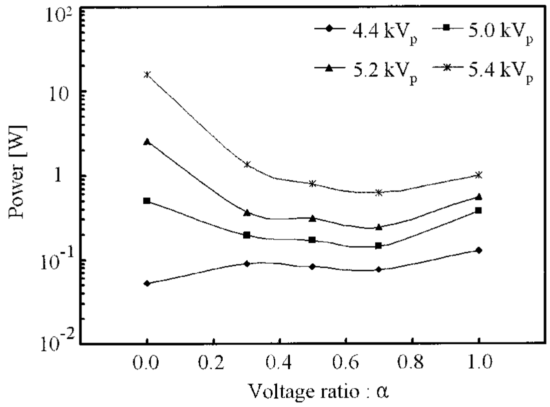


Fig. 9. Power dissipation - voltage ratio curves for different magnitude of applied voltages

The power dissipation was proportional to the voltage ratio at the low applied voltage of 4.4 kV peak, which corresponded to the pre-breakdown region. The DC power dissipation was less than the AC power dissipation at low voltage and vice versa, at a higher voltage. The power dissipation–voltage ratio curves at a given voltage-peak of above 5.0 kV have U-shaped characteristics when the voltage ratio α varies from zero to unity, and the power dissipation is the minimum at the voltage ratio of 0.7. The power dissipation at the constant applied voltage is the maximum under DC voltage, at higher voltages. A similar characteristic of P-V curves has been reported in the literature [8, 11], but no detailed interpretation was given. This behavior of ZnO power dissipation may be applied in the design of ZnO lightning arresters having the minimum power dissipation at operating system voltages.

4. Conclusion

Various behaviors of the leakage current flowing through a ZnO lightning arrester element under combined DC plus AC voltage were analyzed. The experimental results could be concluded as follows: The I-V characteristic curves under the combined DC and AC voltage depend on the voltage ratio α and peak applied voltage and are set between DC and AC voltages. The equivalent resistance of the ZnO element is not only applied voltage-peak dependent but is also affected by the voltage ratio under the combined DC and AC voltage. The crossover phenomenon in the ZnO element under the combined DC and AC voltage was observed in the family of I-V curves and R-V curves. Power dissipation - voltage ratio curves above a certain voltage shows U-shape, and the variation of power dissipation is largely appeared at DC voltage ($\alpha = 0$).

Acknowledgements

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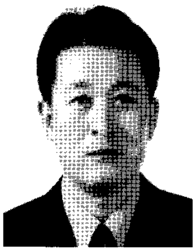

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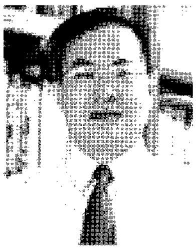

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