Power loss estimation of polymeric housing surge arrester using leakage current and temperature approach

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Abstract. The good operation of metal oxide surge arresters depends on the increment of temperature. If the arresters cannot quickly disperse the absorbed energy into the ambient, arresters temperature may exceed its operating temperature limit. Consequently, thermal runaway occurs and results in power loss. In this paper, thermal characteristics and thermal stability based on power loss calculation were investigated. Applied voltages, leakage current, and temperature were the main parameters consideration. The power loss calculated by the electrical model is the input to the thermal model. The electro-thermal model is used to determine the two intersection points (stable operating point and the thermal instability point) of the power input and heat loss curves. The results show that irrespective of the different magnitude voltages applied to the arrester and different energy ratings for the elements, the power loss occurs at the certain applied voltage.

1. Introduction
The electrical power, especially in high voltage systems are often subject to transient overvoltages due to lightning or switching operation. As a result, the surges travel along the transmission line and can cause damage to the unprotected terminal equipment. Metal Oxide Surge Arrester (MOSA) can limit the overvoltage at chosen protective level. The growth of the recently developed ZnO material over the earlier used silicon carbide (SiC) renewed interest and boosted the use of surge arrester protection.

MOSA is electrical equipment which is one of the most important equipment that can be absorbed electrical energy resulting from lightning and switching overvoltage. Absorbed electrical energy converts to thermal energy in metal oxide varistors and can rise temperature. Therefore, temperature rises which affect the surge arrester performance in normal operating levels [1]. The good operation of MOSA depends on the increment of temperature. If the MOSA cannot quickly disperse the absorbed energy into the ambient, MOSAs temperature exceeds its operating temperature limit.

Consequently, thermal runaway occurs. This phenomenon happens due to the excessive heat generation caused by applied voltages [2]. Owing to the thermal runaway, varistors temperature increment can upset the thermal balance in the MOSA. So the arrester should not only operate stably under the operating voltage but also should operate under the transient condition which is caused by switching and surge overvoltage energy discharge [3].
The empirical equations based on general exponent function to achieve the V-I characteristics and the heat generation of ZnO element models has been prepared in [4]. For this purpose calculations had to be carried out indifferent electro-thermal performance. For this purpose calculations had to be carried out indifferent electro-thermal simulation. The complex function of the current density versus temperature and the electric field has been adopted in [5, 6].

![Figure 1. A sample of the V-I characteristic surge arrester](image)

In low magnitude voltage range, the power input to the varistor has a complex function which is dependent on applied voltage, temperature [1] and degradation of V-I characteristic due to the material variation. Therefore it is difficult to describe power loss by conventional methods precisely. Although several methods have been suggested for MOSA performance prediction, they are not accurate at all the factors above have not been considered together. Using the previous methods, it is not possible to identify V-I-T equation and power loss of MOSA with different characteristics. In other words, alteration of V-I characteristic, which is consequent of material variation, is missed in previous studies which have a very important role in identifying the power loss. The power loss is not predictable only by knowing the temperature, but the degradation of V-I characteristic must be considered to achieve the accurate results [7]. This is the main contribution of this paper. To formalize the effect of material variation, V-I characteristics at different voltages and temperatures for several varistors are obtained by experimental measurements. Varistors to be tested have been collected from new and used MOSAs.

Obtaining V-I characteristics at different voltages and temperatures require high voltage transformer, oven, electrothermal controller, high voltage probe and leakage current meter. Also, determining the V-I characteristics at different temperatures is needed to stabilize the temperature at each stage which is a time-consuming process [8]. Based on the circumstances above, a new method is required to compute power loss curves for investigation of MOSAs electro-thermal performance.

In this paper, thermal characteristics and thermal stability based on power loss calculation were investigated. Applied voltages, leakage current, and temperature were the main parameters consideration.

2. Thermal runaway phenomenon of ZnO surge arrester

In the distribution system, a ZnO surge arrester is subjected to applied voltage, resulting in the resistive leakage current is less than 1 mA flows through the arrester. However, when large surge energy of the power system is absorbed, the temperature of ZnO elements increases, causing the resistance value to decrease. As a result, the leakage current becomes greater and the heat generation increases [9]. Even if the heat generation increases, the temperature rise by surge energy absorption cannot be expected to be below the certain temperature limit intrinsic to the surge arrester.

Since the heat generation in the element raises its temperature, a positive feedback process could occur due to the positive temperature dependence of leakage current as in Figure 1. Namely, the...
temperature rise in the element increases the leakage current, and the increase in the current further raises the temperature. If the applied voltage is moderate, the temperature of the element will reach its equilibrium at the level where the heat generation is balanced with the heat dissipation out from the element [10]. But when the applied voltage exceeds a certain level, the current and temperature have no equilibrium and increase boundlessly to infinity [2, 11]. This is a thermal runaway.

![Figure 2. Thermal runaway phenomenon](image)

3. Thermal stability
Another important characteristic of ZnO surge arrester was the thermal stability (TS) of the arrester. This characteristic can be analyzed by the thermal balance diagram. For a definition of temperature-dependent operating limit, this curve determines the stable and limited thermal performance of arrester according to the thermal balance between the power loss of ZnO varistors and the heat dispersion capability of the houses to the environment [12].

MOSAs are normally operated under maximum continuous operating voltage (MCOV). This condition leads to low power production in elements. This electrical power loss is important for the evaluation of the arrester performance for non-adiabatic conditions. To analyze the thermal balance of MOSAs, first, the power loss model should be obtained. This model determines the operating reliability of MOSAs and their life-spans [13]. So, the power loss characteristics analysis and their model are necessary to investigate the thermal characteristics and stability of ZnO MOSAs.

The voltage and current were measured through experimental. The voltage and current characteristic are used as the main input for watt-loss diagram calculation. The current through of ZnO varistors highly depend on voltage and temperature in the low-current region. Many methods have been studied to approximate the V-I characteristic and electrical power dissipation curve in literature.

This method can be only used in a piecewise manner. To improve the V-I characteristic modeling procedures, a new fitting equation has been developed based on the physical principles of current conduction in the metal oxide material. Also, power dissipation has been modeled as a continuous function of temperature at constant voltage level by the empirical data and interpolation.

4. Electrothermal modeling
The electrothermal model consists of thermal and electrical parts that form together what is called the electrothermal model. Since its electrical characteristics depend strongly on the temperature in the leakage current region of operation, thermal behavior plays a major role in the global performance of the arrester.

4.1. Thermal model
A metal oxide arrester is made of metal oxide varistor disks inside a housing. The housings are made of porcelain or polymeric. The varistor elements were separated from the housing by dry air. So, they can model as an electrical equivalent made of two capacitors, and two resistors appear readily as a valid representation as can be seen in Figure 1. Measurements show that power losses from a heated
body increase in proportion to the temperature difference between it and ambient. The thermal model can be made linear because its temperature rise is limited to near 200°C, where conduction, radiation, and convection can all be combined into equivalent conduction. The heat capacity of the metal oxide elements is also linearized because of the limited temperature range.

\[ \text{Figure 3. The thermal equivalent of a metal oxide surge arrester} \]

In Figure 3, the Te and Th are the symbols for element and housing temperature respectively; \( C_e \) and \( C_h \) are the thermal capacities of the element and housing respectively and \( R_{eh} \) and \( R_{ha} \) the thermal resistances between element and housing, and between the housing and ambient; and finally, \( p(t) \) is the heat source.

The heating effect of the sun is neglected, although it may be important under some circumstances. This model is intended for a station-class type of arrester. In such an arrester, the sun will heat the exposed side more than the shaded side. Depending on the orientation of the arrester, one of the two parallel stacks that may make such an arrester will be warmer than its relative, and thus, will have a greater leakage current.

4.2. Electrical part

When a voltage is applied to arrester terminal, the power loss can be determined by the electrical characteristic of a varistor. This characteristic is dependent on many aspects, but the temperature is the most important. Frequency also plays a major role. The temperature dependence disappears at high current density. In this model, the voltage-current-temperature characteristic is used as the main input. Watt-loss is computed from this data. This voltage-current-temperature characteristic is made up of a series of individual voltage-current curves. These individual curves contain tens of voltage-current points. Interpolation between each point follows Equation 1.

\[ I = p \left( \frac{V}{V_{ref}} \right)^\alpha \] (1)

Where \( p \), \( V_{ref} \) and \( \alpha \) are constants determined by the two points between which \( V \) is positioned. Each V-I curve has a distinct associated temperature. Five such curves, for five different temperature values, are generally sufficient to describe the overall electrical characteristic of metal oxide elements in the leakage current region. To interpolate between two known V-I curves corresponding to two temperatures, the curve of the higher temperature is shifted toward the curve of the lower temperature. The shift applied is computed from the formula Equation 2.

\[ I = e^{(-a+b\Delta T)} \] (2)

Where \( a \) and \( b \) are constants obtained from a point taken on each of the two external curves that have the lowest common voltage, temperature (\( \Delta T \)) is the difference between the required temperature and the temperature of the lower temperature curve. With this procedure, one can compute the current for any given temperature-voltage combination. Thus, it is possible to compute the watt-loss for any voltage across the arrester by the integration of a quarter of the power frequency sine wave. To obtain
the watt-loss of the arrester elements across a temperature range for a fixed value of applied sinusoidal voltage, this integral has to be repeated until enough temperature values are produced. This computed watt-loss characteristic is used as input power for the thermal model of the arrester. The initial temperature of the arrester elements determines their initial power loss. Solving the double RC circuit mentioned above by a numerical method leads to the time response of element and housing temperatures. At each time step, a new element temperature gives a new value of power losses. This method of solving the electrothermal model is similar to putting the arrester across a zero impedance voltage source. In real life, a voltage source always has some impedance. But this simplification is valid since the arrester is temperature sensitive only for leakage current density. The actual voltage drop in a typical network feeding an arrester is negligible because the arrester loses its temperature sensitivity at a current of a few amperes.

5. Research method
The three conditions of 132kV rated polymeric ZnO arresters, namely arrester A, B, and C were subjected to various voltages apply. The leakage currents and also temperatures were measured using 1kΩ resistor and thermography camera respectively. They were captured at the same time. The thermal images and leakage current signals were stored as data acquisition. Each data was processed separately and extracted some features for neural network input and target. The leakage currents were to obtain the parameter leakage current and used for power loss calculation. And the thermal images were processed using NEC Thermal camera software to get some features eg.: maximum, minimum, and temperature distribution.

Figure 4. Experimental setup for energization and measurement of 132kV-rated polymeric arresters.

Figure 4 shows a 132kV polymeric ZnO surge arrester energized by the 500kV phase-to-ground high voltage test system from 70 kV to 120kV with step 1kV, this technique to see possible deterioration in service, the peak value of the total leakage current that flows through the surge arrester when it is subjected to the test voltage, is measured. The test was performed by applying a voltage that was raised, from a value sufficiently low up to reach the test voltage. The peak value of the leakage current should be measured through the voltage drop on a resistive shunt connected in series with the surge arrester. An oscilloscope measured the voltage drop on the shunt resistor, and current waveforms were recorded for further analysis.

At the same time when measured the leakage current, the temperature was also measured using the thermal camera. The captured image of thermal ZnO arrester was analysis using NEC thermal study. Some parameters can be obtained such as maximum temperature and temperature distribution along arrester.

6. Results and analysis
The thermal image and leakage current resulted from measurement were presented. It also presents the data processing and data analysis of thermal and stability of ZnO surge arrester.
6.1. Leakage current

The waveform of the total leakage current ZnO surge arrester is captured for the various applied voltage. Station type of 132 kV polymeric housing ZnO surge arresters were applied continuous voltage from 70 to 120 kV. Total leakage currents were taken using divider resistor 1 kΩ, and temperatures were captured using NEC thermal camera. Example of leakage current waveform shows in Figure 5. The maximum leakage current can reach several milliamperes.

![Leakage current waveform](image)

**Figure 5.** Example of leakage current of 132 kV rated polymer arrester

Figure 6 shows the plotting of voltage-current characteristic of three condition arresters in logarithmic scale, with y-axis is per unit voltage, and the x-axis is the value of the leakage current in milliamperes. It shows the arrester A (triangle mark), arrested B with dot mark and arrester C with cube mark.

The voltage-current characteristic of leakage current of three ZnO surge arrester can be used for an indicator of condition arresters. The horizontal axis is leakage current in milliamperes, and vertical axis are simulated aging level corresponding to the applied voltage from 1 to 120 kV. Based on the voltage-current characteristic of ZnO surge arrester, the maximum of the leakage current of ZnO surge arrester A, B, and C were about 5, 3 and 2 mA when the applied voltage was about 120kV. The leakage current of arrester A more then the others arrested, that means arrester A more degradation compare to the others. In normal condition, it did not exceed 1 mA. The third harmonic value of 1 mA resistive leakage current is about 220 µA, and this corresponds to 109 kV applied. The third harmonic of the resistive leakage current is 100 µA defined as a border between good and caution condition, and 200 µA is the border between caution and faulty conditions.

![Voltage-current characteristic](image)

**Figure 6.** Logarithmic plot of total leakage current of 132 kV rated polymeric arrester for arrester A, B, and C
6.2. **Image processing and temperature extracted**

Figure 7 temperature captured of arrester A, and C using the thermal camera with distance is 1.5 meter. The ambient temperature during the measurement was observed to vary from 27 to 31 °C. The emissivity value as 0.75 for polymeric encapsulated ZnO surge arrester and wind velocity is almost zero because of the experiment conducted in the room.

![Image of temperature distribution](image.png)

**Figure 7.** Measurement of temperature by an infrared camera during the thermal runaway  
(a). ZnO arrester temperature of 30°C after 2 hours applying a voltage  
(b). ZnO arrester temperature of 40°C after 3 hours applying a voltage  
(c). ZnO arrester temperature of 50°C after 5 hours applied a voltage

The temperature distribution of each arrester also presented. As can be seen, the distribution of temperature for all three arresters is concentrated at the top of the arresters element. Since the top of arresters severe from stress, voltage compare to the bottom element.
Figure 8. Temperature influence to leakage current

Figure 8 shows plotting of the leakage current of three arrester samples. At leakage current about 3 mA, all three arresters are almost the same temperature difference; they are between 25 to 30 °C when leakage current increases to 5 mA, the temperature difference for each arrester are increased sharply. Arrester A increase about 50 °C followed by arrester B, and C are about 45 °C and 35 °C respectively.

Table 1. Leakage current and temperature different of arrester samples

| Arrester samples | Applied voltage (kV) | Total Leakage Current (mA) | Ambient Temperature (°C) T | Maxi mum Arrester Temperature (°C) T_a | T - T_a (°C) |
|------------------|----------------------|-----------------------------|-----------------------------|--------------------------------------|-------------|
| A                | 100                  | 3.061                       | 30.2                        | 58.4                                 | 28.2        |
|                  | 103                  | 4.49                        | 30.4                        | 69.3                                 | 38.9        |
|                  | 105                  | 5.532                       | 30.6                        | 76.6                                 | 46          |
|                  | 107                  | 6.41                        | 30.7                        | 78.9                                 | 48.2        |
| B                | 100                  | 3.065                       | 29.6                        | 60.6                                 | 31          |
|                  | 103                  | 3.463                       | 29.7                        | 64                                   | 34.3        |
|                  | 105                  | 4.25                        | 28.9                        | 68                                   | 39.1        |
|                  | 107                  | 5.02                        | 29.2                        | 74.2                                 | 45          |
| C                | 100                  | 3.22                        | 31.5                        | 56.3                                 | 24.8        |
|                  | 103                  | 3.78                        | 31.6                        | 60                                   | 28.4        |
|                  | 105                  | 4.362                       | 31.6                        | 63                                   | 31.4        |
|                  | 107                  | 4.83                        | 31.7                        | 66.2                                 | 34.5        |

Table 1 shows the leakage current and temperature difference of arrester samples. Based on Table 1, the temperature different of arrester A, B, and C are clearly to understand. For all three surge arrester, the temperature differences were significantly influent to the leakage current. It has been affected on V-I characteristic permanently, temperature influence on V-I characteristic is reversible. Electrical resistance decreases with rising temperature, so that, the electrical conductivity of ZnO varistors increase. By increment the electrical conductivity of varistors, leakage current through the
surge arrester increase. On the opposite, reducing arrester temperatures lead to increased electrical resistance. Therefore, electrical conductivity and V-I characteristic returns into original condition.

Table 2. Temperature different and power loss for the various applied voltage

| Arrester | Applied voltage (kV) | Total Leakage Current (mA) | Power Loss (W/cm³) | T-Ta (°C) |
|----------|----------------------|----------------------------|-------------------|-----------|
| A        | 100                  | 3.1                        | 306.1             | 28.2      |
| A        | 103                  | 4.45                       | 462.5             | 38.9      |
| A        | 105                  | 5.5                        | 580.7             | 46        |
| A        | 107                  | 6.4                        | 685.9             | 48.2      |
| B        | 100                  | 3.1                        | 306              | 31        |
| B        | 103                  | 3.4                        | 356.4             | 34.3      |
| B        | 105                  | 4.3                        | 446.3             | 39.1      |
| B        | 107                  | 5                          | 537.1             | 45        |
| C        | 100                  | 3.2                        | 322              | 24.8      |
| C        | 103                  | 3.8                        | 389.3             | 28.4      |
| C        | 105                  | 4.4                        | 457.8             | 31.4      |
| C        | 107                  | 4.8                        | 516.8             | 34.5      |

Figure 9. Power loss function of the applied voltage of arrester A, B, and C

Figure 10 shows the power loss is a function of applied voltage for three arrester sample. As can be seen, the power loss is remains constant at applied voltage 70kV and about 100kV for all three arrester samples. But the power loss increases sharply for applied voltage above 100kV. Increasing about 20kV resulted power loss increases six times for arrester A and four times for arrester B and C. The power loss increases gradually at a voltage below critical value but increases exponentially when a voltage above the critical value.

7. Conclusion
Based on the experimental database has been established to find out the resistive leakage current and power loss at any given applied voltage, operating and ambient temperature. The stable operating and
thermal instability points have been successfully estimated for three different 132 kV rated polymeric ZnO surge arrester of different manufacturers at various applied voltages and ambient temperatures using power input–power loss versus element temperature curve is based on the electro-thermal model. The critical applied voltage has been at points on the power loss curve in-between the stable operating and instability threshold point. The power loss is highly dependent on the applied voltage and can increase exponentially above critical applied voltage.

An obvious observation made from the computed power loss and applied voltages are that its magnitude is higher for arresters with the element of higher energy class. More importantly, it is evident from the results presented in this paper that irrespective of the magnitude of power loss at different voltages applied to the arrester and different energy ratings for the elements.

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