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Analysis of the Working Principle and Characteristic Parameters of Surge Protective Device (SPD) Components

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Abstract: This paper summarizes the working principles of commonly used surge protective device (SPD) components, including zinc oxide varistors, semiconductors, and gas discharge tubes. The characteristic parameters of each component are analyzed, and their critical state parameters are presented. It is suggested that a combination of multiple component's consideration can be given to the design and application of surge protectors. This research provides valuable references for the design and application of SPD.

Keywords: SPD; Zinc Oxide Varistor; Semiconductor; Gas Discharge Tube; Characteristic Parameters

1. Introduction

With the rapid development of communication and electronic information technologies, the widespread use of semiconductor devices and large-scale electronic circuits, as well as the miniaturization of large-scale integrated circuits, it has become increasingly important to address the impact of overvoltage and overcurrent on electronic equipment and protect their delicate components from excessive energy. To mitigate the excessive current and voltage induced by electromagnetic pulses entering electronic systems, a common and effective approach is to employ a combination of various protective components [1]. Common protective components include zinc oxide varistors, semiconductors, and gas discharge tubes, which play a crucial role in surge protective devices (SPDs).

2. Working Principle and Basic Characteristics of Zinc Oxide Varistors

2.1 Working Principle of Metal Oxide Varistors (MOV)

Use to its nonlinear characteristics, the zinc oxide varistors is considered a voltage-limiting protective device. When an overvoltage exists across the varistors, in order to protect the electronic system and dissipate energy, the varistors can maintain the overvoltage at a relatively small voltage value. The characteristics of a zinc oxide varistors that determine its protective performance include current carrying capacity, response time, varistors voltage, junction capacitance, and diameter. The response time of a varistors is on the order of nanoseconds, which can meet the electromagnetic pulse protection requirements of most devices under normal conditions [2].

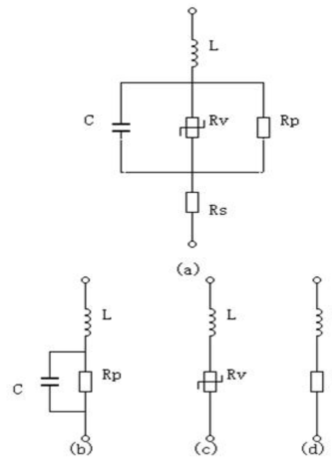

Figure 1. The Zinc Oxide Varistor's Equivalent Circuit Diagram in Different Current Regions

Figure 1(a) shows the equivalent circuit in the full current region, Figure 1(b) can be considered as the equivalent circuit in the small current region. Figure 1(c) is the equivalent circuit in the medium current region, Figure 1(d) shows the equivalent circuit diagram in the large current region. L is the parasitic inductance of the varistors, C is the interelectrode capacitance of the varistors, Rp is the leakage resistance, Rs is a bulk resistance of the zinc oxide, and Rv is a grain boundary layer resistance.

Small current region (leakage region or high resistance region): The voltage/current characteristic curve in the small current region is approximately linear. Observing the current/voltage curve, there is a point with a significant change in curvature in the small current region, which we call the inflection point in the study. When the voltage of the curvature change point is higher than the injection voltage, only a very small current is generated in the varistors, usually less than 1μA· CM^{-2} , and a linear relationship exists between voltage and current at this time. In this region, the medium current in the varistors is very small, and the varistors is in an open-circuit state [3].

Medium current region (clamping working region): The medium current region can also be called the clamping working region. This working region is the core part of the ZnO varistors. A tiny change in voltage amplitude in this region will cause a very large change in current. In this region, the varistors plays a role in stabilizing the overvoltage, its current is relatively larger, and the dynamic resistance is very small.

Large current region (overload region): The large current rising region can also be labeled as the recovery or rising region. The relationship between voltage and current gradually becomes proportional again. In this region, as the current increases, the nonlinear exponent decreases and gradually approaches 1. Figure 2 shows the DC voltage-current density (volt-ampere) characteristic curve of the varistors. [4].

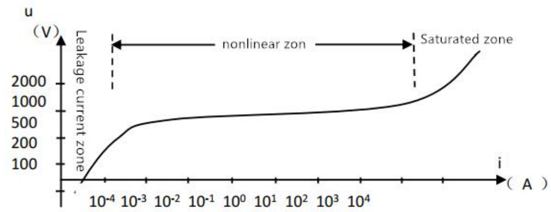

Figure 2. DC Voltage-current Density (Volt-ampere) Characteristic Curve of the Varistors

2.2 Basic Characteristic Parameters and Definitions of Metal Oxide Varistors

Voltage-dependent resistor (U1mA): In common understanding, it refers to the potential difference between the two ends of a varistors under a direct current of 1 mA. Clamping voltage (Uc): After conduction, the varistors will limit the voltage to a certain value, which is called the clamping voltage. Peak overshoot voltage (Up): When an impulse is applied to a zinc oxide varistors with a fast rising edge, the di/dt is very large, and the inductance will be amplified. After conduction, an overshoot voltage Uo will occur. This voltage is superimposed with the clamping voltage Uc to form the peak overshoot voltage Up, that is Up=Uc+Uo=Uc+L·di/dt. A varistors can be approximated as a series-parallel connection of multiple diodes.

3. Diode Characteristics

3.1 Formation of PN Junction

In semiconductors, for n-type semiconductors, free electrons are majority carriers and holes are minority carriers. For p-type semiconductors, the opposite is true. An isolated n-type (or p-type) semiconductor is electrically neutral. When the N-type and P-type semiconductor contacted, because of the concentration gradient of holes and free electrons at interface, there is a large-scale diffusion of holes from the P-region with a high hole concentration to the N-region with a low hole concentration. Conversely, the majority carriers in N-region, electrons, also undergo this type of motion. This carrier motion is called diffusion. As this irreversible spontaneous diffusion process proceeds, in P-region, a large number of holes move out, leaving behind a corresponding number of fixed negative charges. Since there are not enough positive charges to neutralize them, a negative charge region is formed on the p-side of the junction. Similarly, a positive charge region composed of many immobile positive charges is formed on the n-side of the junction. These immobile charges are called space charge, and pn junction or depletion region (as shown in Figure 3).

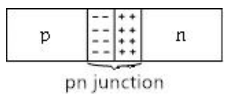

Figure 3. Space Charge Region of PN Junction

3.2 Diode Electrical Parameters

When a diode is operating in an electronic device, there is an external voltage applied across its terminals, causing the pn junction to transition from a thermal equilibrium state to a non-equilibrium state. The electrical characteristic of a PN junction is rectification property, which allows current to flow only in one direction, from the P-region to the N-region. In addition to rectification, the pn junction also has other less significant electrical parameters such as junction capacitance (C) and junction resistance (R) [5].

When a forward bias (positive voltage applied to the p-side) is applied to the pn junction, almost no current flows until the voltage reaches a certain value. Beyond this value, a slight increase in voltage can cause a rapid increase in current. The voltage at this point is called the forward voltage or forward voltage drop, denoted by VF, and the corresponding current is denoted by IF. However, when a reverse bias is applied, initially, there is almost no current, or the current is very small, typically in the microampere range. This current is called the reverse leakage current, denoted by IR, and the corresponding voltage is called the reverse voltage, denoted by VR. The current increases slowly when the reverse voltage is further increased. However, the total current is still tiny when the critical voltage reached, at that time the current increases immediately. The voltage was called reverse breakdown voltage, and this phenomenon is called junction breakdown when a sudden increase in reverse current in the PN junction. The forward voltage is normally less than 1V. However, the voltage of reverse breakdown can range from a few volts to thousands volts, which because of the dopant concentration and other parameters. The current-voltage characteristic (IV curve) was showed in Figure 4 which is a typical silicon PN junction [6].

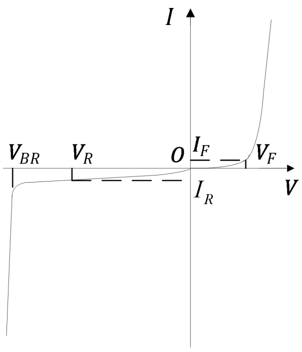

Figure 4. Current Voltage Characteristic (IV curve) of a PN Junction

4. Working Principle of Gas Discharge Tube

The working principle of a gas discharge tube can be explained by the gas gap discharge principle. When an overvoltage is applied across the two electrodes of a gas discharge tube, the non-uniform electric field generated between the electrodes reduces the insulation of the inert gas in the tube. The electric field strength between the GDT increases continuously with the increase of the applied voltage until it exceeds the insulation strength of the inert gas in the tube. At this point, a discharge breakdown occurs between the two electrodes, and the discharge tube changes from an insulating state to a conductive state, discharging a large current to the ground. Subsequently, the voltage between the two electrodes drops sharply and is maintained at the arc voltage level, which is generally only a few tens of volts. Therefore, when the discharge tube is connected in parallel with the electronic equipment, the protected equipment will not be damaged by overvoltage. Figure 5 shows the equivalent circuit diagram of a gas discharge tube. In the figure, LS is the lead inductance of the device, RG is the insulation resistance, CP is the interelectrode capacitance, and SV is a voltage-controlled switch. When the voltage across the two ends reaches the starting voltage, the voltage-controlled switch closes and shorts the circuit, simulating the moment when the discharge tube conducts.

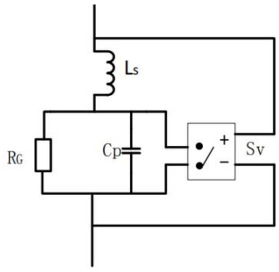

Figure 5. Equivalent Circuit Diagram of Gas Discharge Tube

4.1 Main Performance Parameters of Gas Discharge Tubes (GDT)

The main performance parameters of gas discharge tubes include DC breakdown voltage, impulse breakdown voltage, response time, impulse current withstand capability, insulation resistance, and interelectrode capacitance.

4.1.1 DC Breakdown Voltage

The average voltage value at which a gas discharge tube starts to discharge under a voltage with a rising rate below 100V/s is called its DC breakdown voltage. Due to the inherent randomness of gas discharge in any GDT, the measured DC breakdown voltage will fluctuate. Therefore, the average measured voltage is considered as the DC breakdown voltage after multiple measurements, and the error range is usually specified as ±20%.

4.1.2 Impulse Discharge Voltage

Also known as pulse breakdown voltage, it refers to the operating voltage of the gas discharge tube under transient impulse conditions. It is defined as the voltage at which the gas discharge tube breaks down under a transient voltage pulse with a certain rate of voltage change. It is a dynamic parameter and its value changes with the change of the impulse voltage. Generally, the residual voltage wave's peak value is taken as the impulse breakdown voltage.

4.1.3 Response Time

Response time refers to the time required for the voltage applied to the two electrodes of the GDT to exceed the breakdown voltage value (DC) of the discharge tube and produce the phenomenon of breakdown discharge. The response time of a gas discharge tube can be as fast as tens of nanoseconds and as slow as several seconds, which is the slowest compared to common transient suppressors. The reason is related to the ionization process of the inert gas filled in the discharge tube.

4.1.4 Impulse Current Withstand Capability

It refers to the maximum pulse current value that can pass through a specific waveform and a specified number of pulse currents without causing a significant change in its DC starting voltage and insulation resistance. The current withstand capability of a GDT is extremely high.

4.1.5 Insulation Resistance

Insulation resistance refers to the resistance value of the gas discharge tube when it is not activated. It is usually obtained through a DC voltage test. Typically, the resistance of a GDT can reach gig ohms.

4.1.6 Inter-electrode Capacitance

Inter-electrode capacitance refers to the capacitance between the two electrodes of the discharge tube measured at a frequency of 1 megahertz. The inter-electrode capacitance of a GDT is small, generally in the range of 1-5pF. The inter-electrode capacitance value of a GDT is usually stable and remains basically unchanged with changes in frequency.

4.1.7 Current Carrying Capacity

It refers to the maximum current that the gas discharge tube can conduct without failure when discharging overcurrent. The current carrying capacity of a gas discharge tube can reach 100kA or more.

4.2 Characteristics of Gas Discharge Tubes

4.2.1 Voltage-current Characteristics of Gas Discharge Tubes

As shown in Figure 6, the conduction process of a gas discharge tube generally goes through three stages: non-self-sustained discharge.

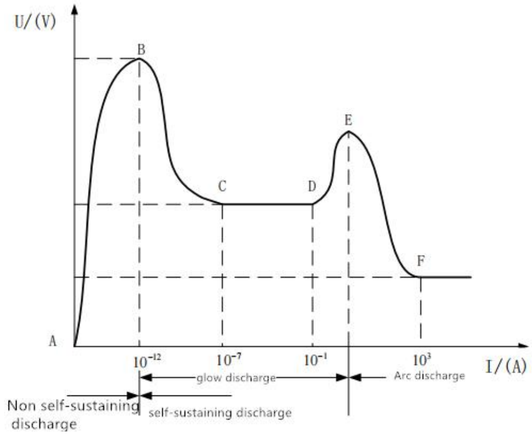

Figure 6. Voltage-current Characteristic Curve of GDT

In the AB segment, a non-self-sustaining discharge occurs. During this phase, the voltage is extremely low in the GDT, and the inert gas within the tube exhibits high insulation properties. Consequently, only a negligible amount of charged particles are in motion, resulting in an almost imperceptible current. In the BE segment, the voltage across the GDT gradually increases until it reaches the breakdown voltage (DC) of the tube. The electric field strength between the GDT electrodes rapidly intensifies, causing the gas insulation to diminish. Subsequently, collisions occur between the electric field and electrons emitted from the GDT's cathode, generating a significant number of positive ions. These ions continue to bombard the cathode, leading to a rapid increase in current within the GDT and the onset of a glow discharge. Finally, in the EF segment, the sustained bombardment of the cathode by positive ions causes a rapid increase in the cathode's temperature, stimulating the emission of more electrons. As a result, the voltage across the GDT drops precipitously, transitioning into an arc discharge phase, with the voltage stabilizing between 20-60V.

4.2.2 Response Characteristics of Gas Discharge Tubes

When a voltage is applied across a gas discharge tube, due to the time required for the ionization of the inert gas inside the tube and the reaction of the cathode, there is a certain delay in the actual discharge of the tube. This delay time is called the response time. Given the actual discharge voltage of the gas discharge tube under a given steepness du/dt, the response time can be determined by the following equation (1):

$$\Delta t = \frac{u_{fr}}{du/dt} \quad (1)$$

Where, ufr is the actual discharge voltage, du/dt is the voltage change rate.

5. Conclusion

Surge protection devices play an increasingly critical role in modern construction. The selection and application of suitable surge protective devices are crucial for effective lightning protection. By understanding the working principles and characteristic parameters of surge protective devices components such as zinc oxide varistors, semiconductors, and gas discharge tubes, engineers can make informed decisions when selecting the appropriate components for various surge protective devices. Only through such careful selection can system operation be ensured and electronic equipment be reliably protected.

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