2004 IEEE International Conference on Industrial Technology (ICIT)

Varistor as a Surge Protection Device for Electronic Equipments

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Abstract- This paper is aimed at presenting a design of a varistor-based protection circuit for load-connected electronic equipment. The varistor I-V characteristics are described-for the first time- in five regions. Not only the protection-circuit parameters but also the varistor parameters are determined according the load being protected. Because of the nonlinearity of the protection circuit, the describing equations for load and varistor currents and voltages are solved numerically. Different waveforms of the input voltage with and without surge superimposed on the normal operating voltage are investigated. In all cases, the protection circuit has limited the load voltage to a safe value irrespective of how high the input voltage with the superimposed surge.

1. INTRODUCTION

There are several different sources of overvoltages that are of interest to electronic circuit designers: lightning strokes, electromagnetic effects of detonation of nuclear weapons, high-power microwave signals and switching reactive loads which can cause failure, permanent degradation, or temporary malfunction of electronic devices or systems. Detailed properties of these transient voltages are reported [1]-[6].

Surge protective devices are designed to reduce potentially damaging short-duration transients present on utility power lines, and any other data or control lines connected to electronic equipment. One common misconception is that electronic equipments are designed to receive zero transient voltage surges from power or data lines. This is not the case. With 220 V_{rms}-computer systems, reducing transients to levels of approximately 150% to 300% of line voltage (maximum permissible voltage) will prevent equipment damage [3]. A commonly used in suppressing many transient voltage surges is the Metal Oxide Varistor (MOV). An MOV is actually a non-linear resistor with certain semi-conductor properties. The MOV remains in the "OFF," or non-conducting state until a surge appears on the line where it conducts to clamp the voltage in excess of the maximum permissible value.

2. VARISTOR I-V CHARACTERISTICS

2.1 Review of the literature

There are three characteristic regions for MOV operation, Fig. 1. At very small currents less than 0.01mA (region 1), the varistor behaves like a simple resistor, called R_{Leak}; leakage resistance which is about 10^3 MΩ. At very large currents greater than 10^4 A (region 3), the bulk resistance of the device, R_{Bulk}, dominates the varistor response. The bulk resistance reaches about 0.01 Ω and the varistor approximates to a short circuit followed by a varistor failure. Between these regions (region 2), the I-V characteristics of the varistor follows the exponential equation (1). Modern metal oxide varistors have values for α between 25 and 60 [1].

$$I = KV^{\alpha} \qquad (1)$$

where

I Current through varistor
V Voltage across varistor
K Constant (depending on varistor type)
α Nonlinearity exponent (a measure of nonlinearity of the characteristics curve)

The starting point of region 2 corresponds to a 1 mA varistor current at a voltage $V_{N(AC)}$, while the end point defines the maximum

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clamping voltage V_c at the peak varistor current I_{pk}.

2.2 Proposed Modeling by Adding Two Transition Regions

Two additional regions are suggested; region 4 to cover the mismatch between regions 1 and 2 and region 5 to cover the mismatch between regions 2 and 3, Fig. 1.

Equation (2) is proposed to cover region 4, the downturn transition between regions 1 and 2 and region 5, the upturn transition between regions 2 and 3.

$$Log\,(V) = b_1 + b_2\,Log\,(I) + b_3\,e^{-\log(I)} + b_4\,e^{\log(I)} \tag{2}$$

This means that the characteristic curve for any specific varistor can be described by the parameters b1 ... b4 in the transition region. Of course, the parameters b1 ... b4 for region 4 differ from those of region 5. Thus, region 4 extends over the current range 10^{-5} A-10^{-3} A and region 5 starts at a current value of I_{pk} and ends at 10^4 A. Eqn. (2) has been suggested before [7] but the coefficients b1 ... b4 were determined only for the upturn region. Figure 1 shows the typical V-I characteristic curve for the five regions of the varistor type S20K275.

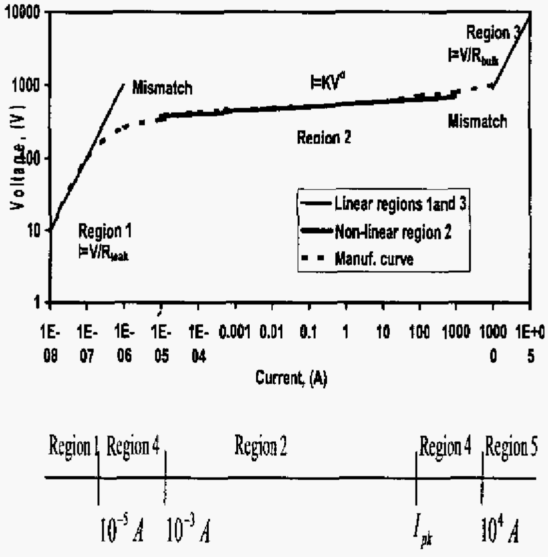

Fig. 1. Five-region varistor characteristics.

3. VARISTOR PARAMETERS

3.1 Rated RMS Voltage $V_{M(AC)}$

It is defined as the maximum permissible continuous sinusoidal RMS voltage which may be applied on the varistor and it should be at least 1.25 times the RMS value of the supply voltage V_s [1]. The voltage value $V_{M(AC)}$ appears in the varistor code (Appendix A).

3.2 Maximum Clamping Voltage V_c

The maximum clamping voltage V_c of the varistor is the peak permissible voltage which appears across the varistor at the peak current I_{pk} in the presence of voltage surge. It is usually chosen 150% to 300% of the peak supply voltage ($\sqrt{2}\,V_s$).

3.3 Peak Surge Current I_{pk}

The varistor peak current I_{pk} is the limiting value beyond which the varistor commences its operation in the transition region 5. The peak value I_{pk} defines the varistor size as denoted in the varistor code (Appendix A).

3.4 Nominal Voltage $V_{N(AC)}$

It is the voltage across the varistor at a current of 1 mA and this corresponds to the point at which region 2 starts.

4. PROTECTION CIRCUIT PARAMETERS

Figure 2 shows the proposed varistor-based circuit for protecting resistive loads with the aid of a series resistance R_s.

4.1 Series Resistance R_s

A series resistance R_s is needed to form a voltage divider with the load resistance R_L in presence of the voltage surge. The series R_s is selected such that the voltage across the load in absence of the surge does not drop below 95% of its rated value. It is common to determine the resistance d from the following formula [1]:

$$R_s \leq 0.053\ R_L \tag{3}$$

4.2 Maximum Transient Voltage V_{in}

It is the maximum expected crest value of the input voltage V_{in} including the transient overvoltage. V_{in} is clamped to a value down to the varistor voltage V_c and defines the peak current I_{pk} as:

$$I_{pk} = (V_{in} - V_c)/R_s - I_L \qquad (4)$$

where I_L is the load current during the voltage surge and is expressed as:

$$I_L = V_c / R_L \qquad (5)$$

5. Numerical Modeling

5.1 Varistor Model

In the operating region of the selected varistor, region 2, the varistor obeys the exponential equation (1). Normally α is determined according to eqn. 6 from pair of points on the I-V characteristic curve corresponding to 1 mA and 1 A currents.

$$\alpha = [Log(I_2) - Log(I_1)]/[Log(V_2) - Log(V_1)] \qquad (6)$$

Once the value of α is determined, the constant K is determined according to eqn. (7) at the point of $V_{N(AC)}$ voltage and 1 mA current.

$$Log(K) = Log(I_1) - \alpha Log(V_1) \qquad (7)$$

where $I_1 = 1mA$ and $V_1 = I_1 = V_{N(AC)}$

To determine the parameters b1 ... b4 describing region 4 of the selected varistor, four points are selected in this region assuming the V-I characteristics follows eqn. (1). This formulates four simultaneous equations whose solution determines the coefficients b1 ... b4 of this region.

Similarly, the parameters b1...b4 describing region 5 of the selected varistor are determined where another four points are selected in this region assuming the V-I characteristics follows eqn. (1). This formulates four simultaneous equations whose solution determines the coefficients b1... b4 of this region.

5.2 Surge Voltage Model

A simple approximate mathematical expression for the IEC 60-2, ANSI/IEEE Std 4-1978 and ANSI C62.1-1984 transient voltage waveform $v_{sg}(t)$ as specified in the standards [1] is given by the following expression

$$v_{sg}(t) = A V_P \{1 - \exp(-t/\tau_1)\} \exp(-t/\tau_2) \qquad (8)$$

where $t \geq 0.0$

τ_1 is the time constant for the leading edge of the wave.

τ_2 is the time constant for the tail of the wave.

V_p is the peak surge voltage value.

A is a constant necessary to make the maximum value of $A\{1 - \exp(-t/\tau_1)\}\exp(-t/\tau_2)$ to be unity.

6. CASE STUDY

Figure 2 shows a circuit consisted of a load R_L simulating the electronic device (assumed 500Ω) fed from a supply voltage V_s (220 V rms value) along with a surge voltage V_{sg} (2 kV crest value) superimposed on V_s at the peak value (i.e. the peak value of the input voltage $V_{in} = \sqrt{2}\,V_s + V_{sg} = 2.31\,kV$). The load is protected by the proposed protection circuit being composed of a protective varistor connected in parallel with the load and a series resistor R_s to limit the current through the varistor to a safe value.

6.1 Selection of Varistor

- Continuous rated voltage, $V_{M(AC)} = 1.25 * 220 = 275$ V, where $V_s = 220\,V$.
- Maximum clamping voltage V_c is 150-300% of the peak supply value ($220\sqrt{2}$). For a

safe design, V_c is chosen about 230% of the peak value $220\sqrt{2}$, i.e 710 V.

- According to eqn. (3), the series resistance R_s is less than or equal to 26.5 Ω. A value of 25 Ω is selected.
- From eqn. (5), the load current I_L during the voltage surge is 1.42 A.
- The peak surge current through the varistor

From eqn. (4), the varistor current is found to be 62.62 A. The next value in data sheet is 100 A. Thus the selected varistor type is S20K275, where the disk diameter is 20 mm corresponds to I_{pk} of 100 A varistor current. The nominal voltage $V_{N(AC)}$ for the S20K275 varistor is 430 V from the varistor data sheet.

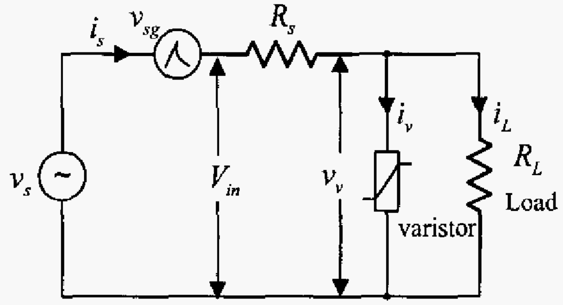

Fig. 2 Protective circuit.

6.2 Protection Limit of the Selected Varistor

With the selected varistor type, the circuit capability is extended to protect the load against the higher surge voltage of crest value $V_{in\,\mathrm{limt}}$, which is expressed by the following equation:

$$V_{in\,\mathrm{limt}} = I_{pk}R_s + V_c[\frac{R_s}{R_L}+1] \qquad (9)$$

For the selected Varistor, $V_{in\,\mathrm{limt}}$ =3245.5 V. If V_{in} exceeds $V_{in\,\mathrm{limt}}$, the varistor current increases over the peak current and a change of the selected varistor is a must [8] and another one having a higher clamping voltage V_c and a higher peak current I_{pk} should be selected.

6.3 Representation of the Selected Varistor

At very small currents, less than 0.01 mA the S20K275 varistor is in its high resistance R_{leak} mode, region 1, $R_{leak} = 1000\,M\Omega$.

At very large currents, more than I_{pk} (=100 A), the S20K275 varistor response is dominated by the bulk resistance R_{bulk}, region 3, $R_{bulk} = 0.01\Omega$.

For the selected S20K275 varistor $\alpha = 31$ and $K = 2.304x10^{-85}$. Table 1 gives the varistor parameters in regions 4 and 5.

Table 1: Regions 4 and 5 coefficients

Region	4	5
b1	2.1202	2.7225
b2	- 0.1219	0.026
b3	- 0.0016	0.0023
b4	3.904	0.0046

Figure 3 shows the proposed five-regions V-I characteristic curve of S20K275 type varistor as compared with the manufacturer characteristic curve. It is satisfying that both characteristics are very close.

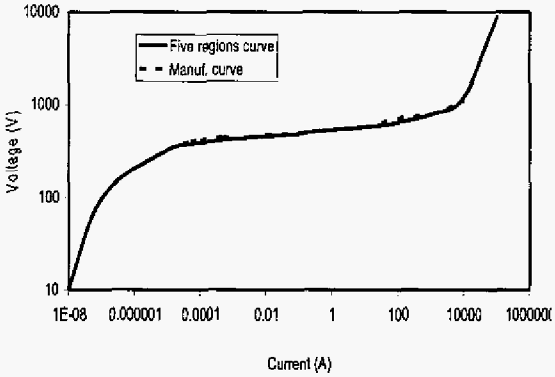

Fig. 3 Proposed five-regions V-I S20K275 varistor characteristics.

6.4 Representation of Surge Voltage

The parameters of transient voltage waveform $v_{sg}(t)$ in eqn. (8) have the following values:

$$\tau_1 = 0.4074\,\mu s$$
$$\tau_2 = 68.22\,\mu s$$
$$V_p = 2.0\,kV$$
$$A = 1.037$$

6.5 Numerical Solution of Describing Equations

The input voltage to the load is represented by the surge voltage superimposed at the peak of the normal sine waveform after 1.25 complete cycles as:

$$v_{in} = \sqrt{2}V_s \sin(\omega t) + v_{sg}(t) \qquad (10)$$

Applying Kirchoff's voltage law to the circuit of Fig. 2,

$$v_v = V_{in} - R_s i_s \qquad (11)$$

$$i_s = i_v + i_L \qquad (12)$$

where v_v and i_v are the instantaneous voltage and current of the varistor, respectively.

In regions 1 and 3 the relation between v_v and i_v of the varistor is linear and described by its leakage R_{Leak} and its bulk resistances (R_{Leak}, R_{Bulk}). Subsequently, equations (10)-(12) are solved directly to find the circuit variables. However, in regions 2, 4 and 5 these equations are non linear due to the non linear relationship between v_v and i_v. Therefore, equations (10), (12) are solved numerically along with eqns. (1) and (2) of the selected varistor. The well known Newton Raphson method is found suitable for the solution of these equations.

7. Simulation Results

Three different waveforms of the input voltage V_{in}, Fig. 2, and the respective response of the designed protective circuit are investigated.

7.1 Sinusoidal Voltage of 220 V rms value (normal operating voltage)

No surge voltage V_{sg} is applied. The varistor is non conducting as the peak value of the input voltage (√2 220) is less than nominal voltage $V_{N(AC)}$ (430 V). The load voltage is almost the same as the input voltage, Fig. 4, provided that the voltage drop across R_s is negligible. The load and varistor currents are shown in Fig. 5 where the load current varies sinusoidaly as the input voltage and the varistor current is the leakage value.

7.2 Voltage Surge of crest value 2 kV

No supply voltage is applied (V_s=0) and the varistor is conducting due to surge voltage. Because the clamping voltage V_c of the varistor is (611V), the input voltage is reduced to a level of approximately 196% of the peak value of supply voltage ($220\sqrt{2}$ V) with no damage for the load connected equipment as shown in Fig. 6. The peak current through the varistor I_{pk} is 54.31 A while the load current I_L is 1.22 A (=611V/500Ω). The varistor current follows the surge voltage while the load current remains constant at 1.22 A, Fig. 7.

It is must be noted that the clamping voltage is less than the maximum clamping voltage of the S20K275 varistor (710 V) because the varistor current did not reach the varistor peak current I_{pk} (100 A).

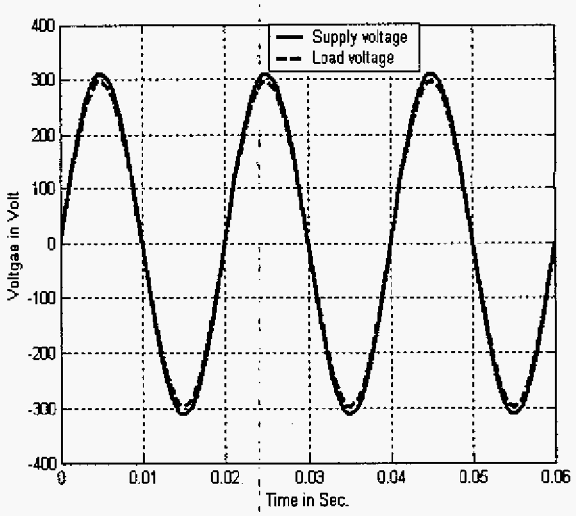

Fig. 4 Input and load voltages.

7.2 Voltage Surge of crest value 2 kV

No supply voltage value V_s is applied and the varistor is conducting. Because the clamping voltage V_c of the varistor is (611V), the input voltage is reduced to level of approximately 196% of line voltage (220 V rms value) with no damage for the load connected equipment. The peak current through the varistor I_{pk} is 54.31 A while the load current I_L is 1.22 A (=611V/500Ω).

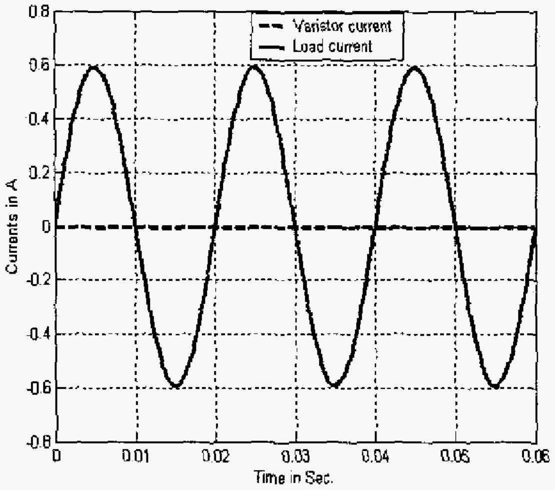

Fig. 5 Load and varistor currents.

7.3 Voltage surge Waveform of Crest Value 2 kV Superimposed on the Normal Operating Voltage of 220Vrms Value

Figure 8 shows the input voltage composed of the normal operating voltage and surge voltage. The effect of the varistor in limiting the load voltage to the clamping value is shown in Fig. 9. The clamping voltage V_c is 613.8 V, the peak varistor current is 66.65 A as shown in Fig. 10 and the peak value of the load current is 1.2277 A as shown in Fig. 11.

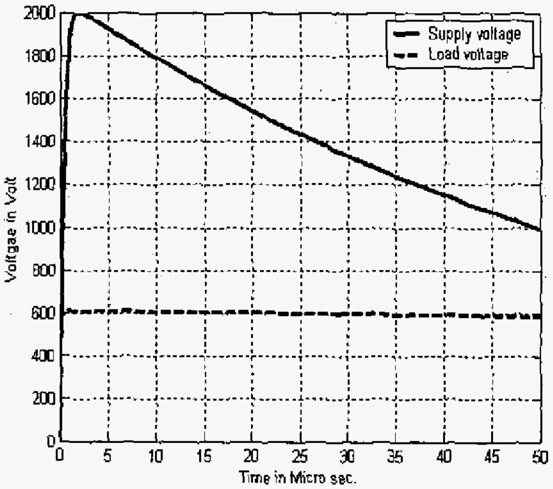

Fig. 6 Input and load voltages.

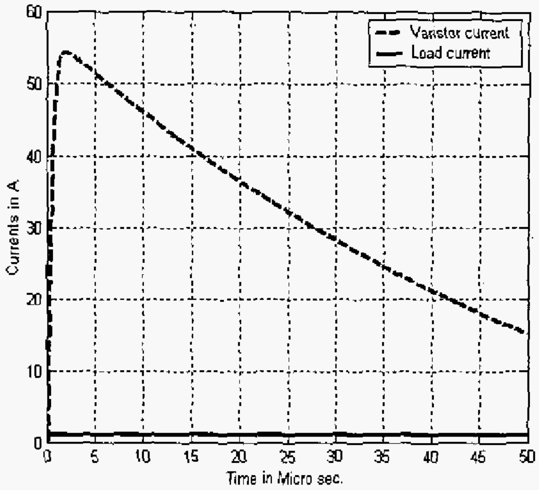

Fig. 7 Load and varistor currents.

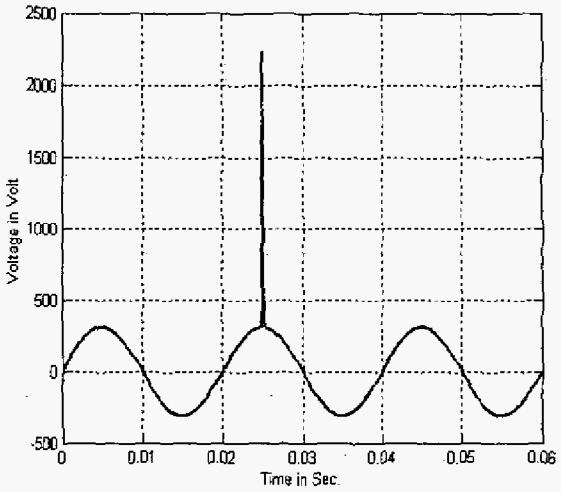

Fig. 8 Input voltage.

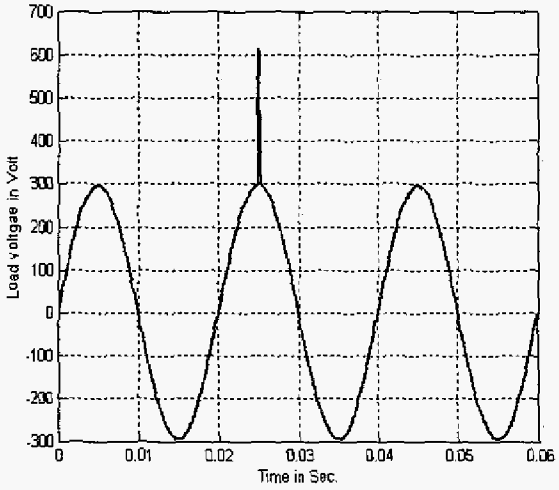

Fig. 9 Load voltage.

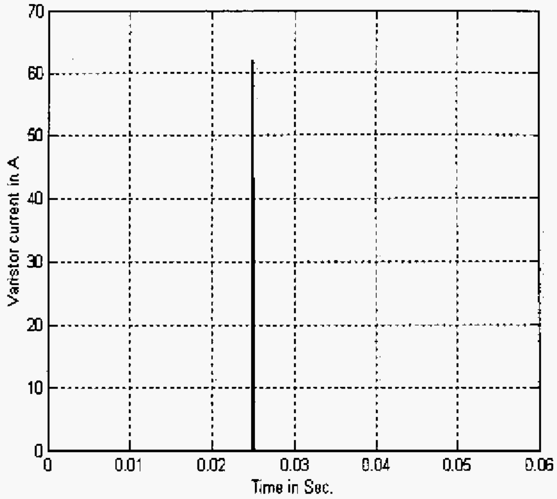

Fig. 10 Varistor current.

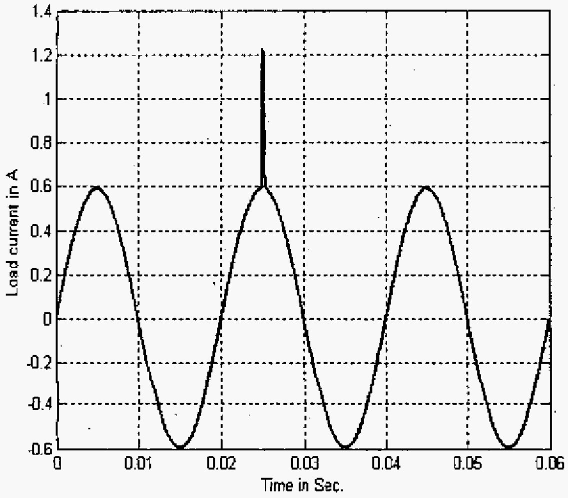

Fig. 11 Load current.

CONCLUSIONS

1) The varistor current-voltage characteristics are described -for the first time- in five regions from leakage current to short circuit-current value.
2) A design procedure for varistor-based protection for load-connected electronic equipment is presented. Not only the protection-circuit parameters but also the varistor parameters are determined according to the load being protected.
3) Numerical solution of the nonlinear equations describing the load and varistor currents and voltages is presented.
4) The designed protection circuit worked well for different waveforms of the input voltage and the load voltage never exceeds the safe value in presence of a surge voltage superimposed on the supply voltage at the input.

Appendix A

Varistor Coding

The manufacturers commonly use a standard identification or code to specify the rating and the dimensions of the varistor as follows:

Varistor SIOV- S 20 K 275
Varistor SIOV- B 32 K 275

Varistor	*Variable Resistor*
SIOV	SIemens-Metal Oxide Varistor
S/B	Disk varistor – round/Block
20/32	Disc Diameter in mm as determined by the current I_{pk} .
K	Tolerance of nominal voltage (1mA) ± 10%
275	Rated rms voltage, $V_{M(AC)}$.

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