SILICON CARBIDE VARISTORS

It has long been known that silicon carbide will, under suitable conditions of contact, exhibit a non-linear relationship between current and voltage. This may readily be demonstrated by measuring the voltage-current characteristic of a mass of small particles of silicon carbide compressed between metallic electrodes. As the voltage is increased from zero the current increases, at low voltage in direct proportion to the voltage and then much more rapidly. If the number of particles in the mass is large and the distance between electrodes large compared with the dimensions of the particles the non-linear resistance of the device is independent of polarity.

Experiments upon single particles with suitably made contacts indicate that the body resistance of the particle is small, ohmic, and independent of polarity.

The non-linear conduction exhibited by the mass of particles results from the voltage-dependent resistances at the point-to-point contacts between the granules of silicon carbide. The overall resistance characteristic may be thought of as due to large numbers of non-linear resistance contacts arranged at random in series and parallel. In a statistical sense the aggregate displays no dependence upon the direction of current flow. This varistor is an example of a "symmetrical non-linear resistor."

The simple device of containing a mass of silicon carbide particles under pressure between electrodes does not have the stability of characteristic under use conditions to afford wholly reliable circuit elements.

In 1930, McEachron (see *Journal A.I.E.E.*, Vol. 49, 410 [1930]) described a silicon carbide ceramic non-linear resistor to which the name Thyrite was given. The material consists of silicon carbide particles bonded in a ceramic matrix. Similar materials are known under various names such as Metrosil and Atmite.

The essential steps of manufacture are these: suitable silicon carbide particles, clay and water, sometimes with a minor constituent such as carbon, are mixed to form a plastic mass. The mass is partially dried and forced through screens to obtain a slightly damp granular powder. This material is compressed under high pressure into desired shapes, generally flat disks or rods. These pieces are further dried and heat treated in a reducing atmosphere at a temperature in the neighborhood of 1200 deg cent. The fired pieces are hard and strong and have mechanical properties quite similar to those of dry process porcelain. Electrodes on the opposite plane faces are provided by spraying or Schooping a layer of metal such as brass, copper, aluminum, or tin. The piece is then usually impregnated with a moisture-repellent organic substance to prevent pickup of water, which adversely affects their electrical stability.

The electrical properties of the product are profoundly affected by the parameters of process: materials, particle size, moisture content, forming pressure, and especially temperature, time, and atmosphere of the heat treatments. The products of different manufacturers differ somewhat in electrical properties, most importantly in the degree of non-linearity, and the characteristics of Fig. 8 are to be taken only as generally indicative. The current-voltage characteristic shown is closely represented by the equation

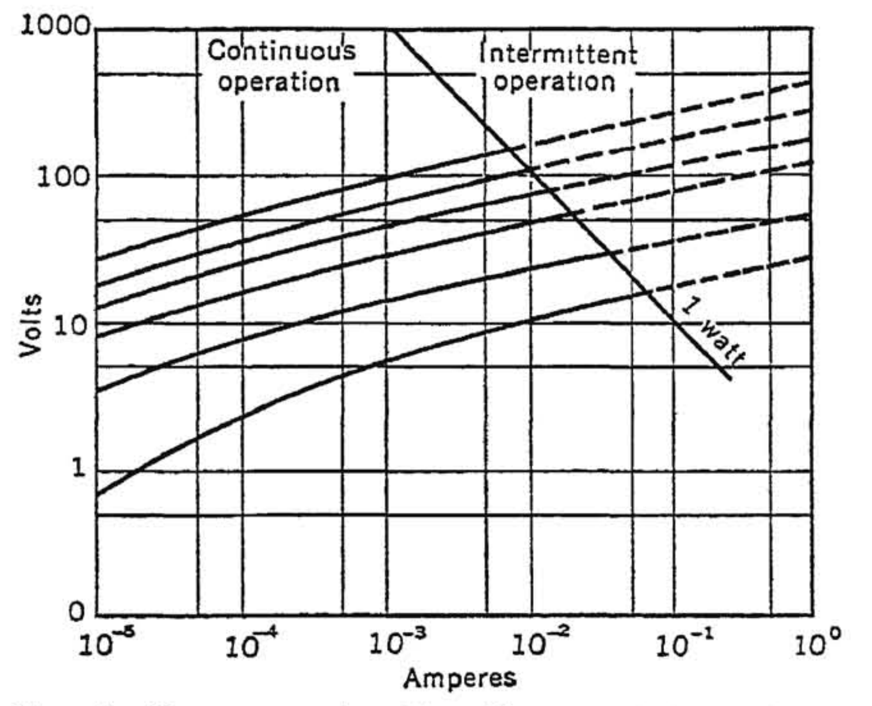

FIG. 8. Representative D-c Characteristics of Some 3/4-in.-diam. Silicon Carbide Varistor Disks

$$I = C_1E + C_2E^n$$

where I = current through the piece, E = voltage applied to the piece, C_1 and C_2 are constants depending on the material and geometry of the piece, and n is an exponent the value of which depends on various factors in the manufacturing process and generally lies between 3.5 and 5.0. Some manufacturers indicate values of n as high as 7.0 but only for pieces having resistances much above the range indicated in Fig. 8.

The variation of characteristic through control of manufacturing processes and geometry of the piece permits coverage of an enormous range of current and voltage. This range may be further extended by connection of pieces in series or parallel. It is to be noted from Fig. 8 that as the resistance of the piece decreases the value of n decreases also, and this being typical of all manufacturers' products may be considered an inherent characteristic of the presently made material. In consequence it is not possible with this device to obtain marked non-linearity at low voltage.

In common with semiconductors the silicon carbide varistor exhibits a negative temperature coefficient of resistance. The coefficient does not have a single value but varies both with the material and with voltage and temperature. The values of the coefficient at constant voltage cover a spread of from 0.3 per cent to 0.9 per cent per degree centigrade in the normally used range of temperature. The higher values of temperature coefficient are observed at the lower voltages.

At high frequencies consideration should be given to the presence of a capacitance effectively in parallel with the non-ohmic resistance. The exact value of this capacitance is determinable only by measurement, but the order of magnitude may be calculated by assuming the material to have a dielectric constant of 30 to 200.

Commonly used shapes are rods and disks. Small disks and rods may be furnished with leads soldered to the metallic electrodes on the faces of the piece. Disks are also made with holes in the center and clamped together with wiring terminals by means of a central bolt. Disks and rods of all sizes are used with spring clip mountings which furnish mechanical support and electrical connections.

When used under high humidity conditions, or at low currents, the organic impregnant, referred to in the description of the fabricating process, may not be sufficient protection against moisture and further precautions may be necessary.

Approximate values of mechanical and thermal properties of importance in circuit element design are as follows:

Bulk density	2.35 grams per cu cm
Compression strength	15,000 to 23,000 lb per sq in
Specific heat	0.17 to 0.21 cal per gram per deg cent
Thermal conductivity	0.0034 cal per cm per sec per deg cent

Requirements on the current-voltage characteristic for a particular application may be stated in a number of ways; the following are commonly used.

(*a*) The voltage E_1 at a current I_1 shall be greater than some value, and the voltage E_2 at a current I_2, where I_2 is greater than I_1, shall be less than some value. This statement of requirements contains implicitly a requirement as to the minimum value of n.

(*b*) The voltage at a given current I shall be equal to a value $E \pm X$ per cent, and the value of n shall lie within certain limits throughout a range of current.

It is to be noted that considerable differences in characteristic may exist between pieces meeting a set of such requirements. In commercial manufacture the range of voltage at a given current commonly runs ±20% about the average. Accuracy of meters used in checking requirements is important since errors in voltage readings are to be multiplied by n in determining their effect on current readings.

Self-heating resulting from power dissipation in the varistor lowers its resistance (negative temperature coefficient of resistance), but this effect is in general reversible; that is, no permanent effects on the characteristic are produced by moderate heating, say from 100 to 150 deg cent. The safe upper limit of heating is oftentimes determined by the moisture-resistant organic compound used as an impregnant. As shown in Fig. 8, 1.0 watt for a disk of 3/4-in. diameter suspended in free air at 50 deg cent is a limit recommended by one manufacturer. Very heavy transient currents may alter permanently the characteristic, usually in the direction of decreasing the resistance.

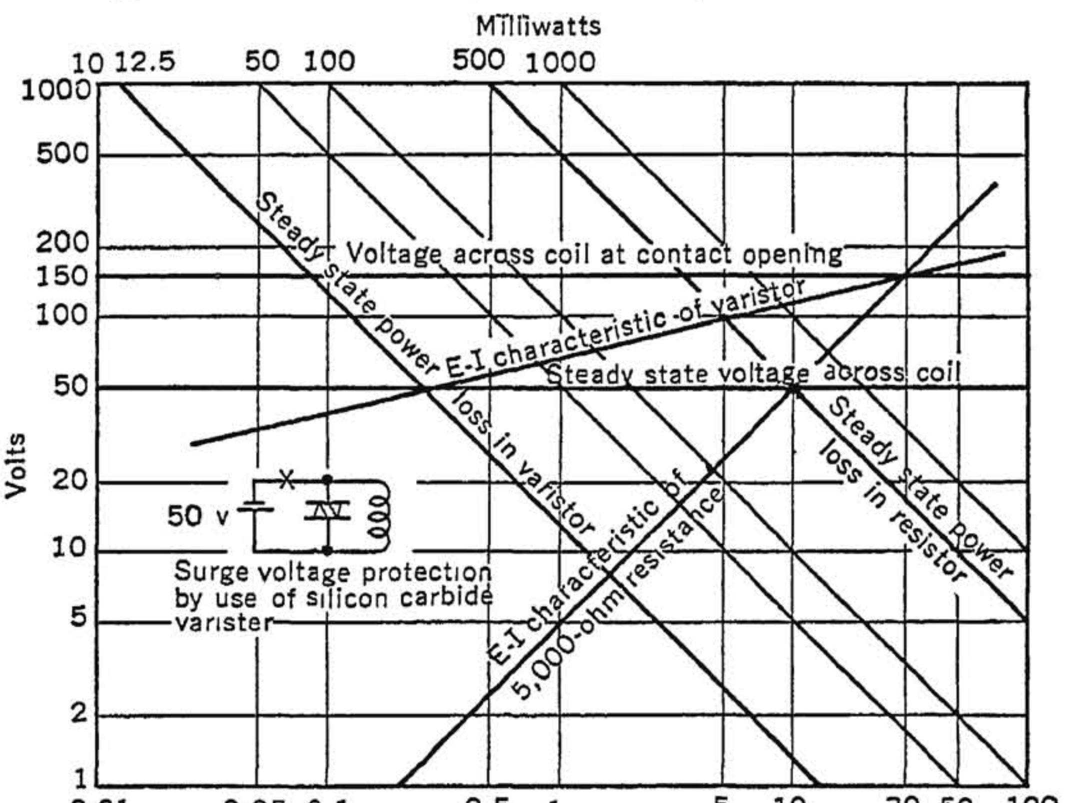

FIG. 9. Surge Voltage Protection by Use of Silicon Carbide Varistor

APPLICATIONS. (1) A silicon carbide varistor connected across the terminals of an electromagnetic winding acts to limit the surge voltage generated when the field is opened. As shown in Fig. 9 the maximum value of voltage across the varistor may be determined from the point on the voltage-current characteristic corresponding to the steady-state value of current I_0 in the winding. As compared with an ordinary resistance shunt across the winding to secure the same voltage-limiting effect, the varistor dissipates much less power when the coil is steadily energized.

(2) In certain carrier telephone system filters exposed to high incoming voltage, the condenser of a high-Q combination of coil and condenser has been protected by a varistor in shunt.

(3) Some of the smaller telephone switchboards have line lamps connected directly in the subscriber's loop for signaling. These line lamps are exposed to electrical disturbances that may be impressed on the outside lines, and if the disturbances are severe enough the lamps may be burned out. Silicon carbide varistors have been used very effectively in parallel with the lamp to bypass large incoming surges. The high resistance of the varistor at the normal signaling level has no appreciable effect on the lamp illumination.

(4) Use is made of varistors to protect contacts controlling inductive circuits from the deleterious effect of sparks resulting from the opening of such circuits. Usually the varistor is connected across the winding rather than across the contact to avoid continuous current drain. Though such an arrangement is useful it is not a satisfactory general solution of the problem. The varistor increases the release time of the relay or switch magnet, though not to the extent that an ohmic resistance of equivalent spark quenching action would do, and it does not entirely eliminate high-frequency oscillations across the opening contact due to the associated wiring.

BIBLIOGRAPHY

McEachron, *J. A.I.E.E.*, Vol. 49, 410 (1930). (Thyrite.)
Fairweather, *J. A.I.E.E.*, Pt. I, Vol. 89, 499 (1942). (General. Contains bibliography of 59 items.)
Ashworth, Needham, and Sillars, *J. A.I.E.E.*, Pt. I, Vol. 93, 385 (1946). (General. Contains bibliography of 25 items.)
Brownlee, *Gen. Elec. Rev.*, Vol. 37, 175 (1934); Vol. 37, 218 (1934). (Calculation of circuits.)
Grisdale, *Bell Labs. Record*, Vol. 19, 153 (1941). (General.)
Vigren, *Telegrafstyrelsen*, No. 7, Vol. 9, 138 (1942). (Contact protection.)
Royal Aircraft Establishment Issue 4, August 1946, Bibliography of Literature on Rectifiers and Semi-conductors.