Lawrence Berkeley National Laboratory

Recent Work

Title

Varistors: A Useful Tool for Superconducting Magnet Quench Protection

Permalink

<https://escholarship.org/uc/item/9m58583c>

Journal

IEEE Transactions on Applied Superconductivity, 31(5)

ISSN

1051-8223

Authors

Strauss, Bruce P
Green, Michael A

Publication Date

2021-08-01

DOI

10.1109/tasc.2021.3058225

Peer reviewed

Varistors: A Useful Tool for Superconducting Magnet Quench Protection

Bruce P. Strauss , *Fellow, IEEE*, and Michael A. Green , *Senior Member, IEEE*

Abstract—A perfect varistor is a constant voltage resistor as a function of current through the resistor. A perfect varistor can't exist, because its resistance would be infinite at zero current. In electronic devices, varistors are often used as surge protectors. A varistor can be used in place of an ordinary resistor as the discharge resistance across superconducting coil sections. When used this way, the integral of $I^2 dt$ during the discharge can be reduced by almost one third. When a varistor is used for quench protection of coils that are coupled to shorted secondary circuits the integral of $I^2 dt$ can be reduced much more. This can be a key factor when coil current densities and stored energies are high as in many potential HTS magnet systems. This paper discusses the types of varistors that are commercially available and their characteristics.

I. INTRODUCTION

A varistor changes resistance depending on the current that passes through it [1]. A varistor is made from materials that are semi-conductors. Semi-conductor behavior was first described by Braun in metal sulfide crystals in 1874 [2]. These materials were used as detectors for radio messages as early as 1894 [3]. As a boy, I can remember my father talking about hearing voice transmitted by radio waves in 1915 on a crystal radio receiver that used a galena (PbS) crystal. He was ~15 km from a radio station located in San Jose California that started broadcasting voice around 1912. The voice broadcasts were heard by tens of thousands of people who attended the World's Fair in San Francisco California in 1915, which was ~85 km from the San Jose transmitter. In 1921, this station went on the air as KQW at a frequency 740 kHz. The station's call letters were changed to KCBS in 1949.

To first order, a varistor is a constant voltage device. A varistor behaves like the forward voltage of a diode except that the forward voltage is the same when the current flows in both directions. The first varistors were back to back rectifiers made from stacks of Cu and CuO or Cu and GeO₂ hooked up in an antiparallel configuration (see the left side of Fig. 1) [4]. The use

Fig. 1. The Varistor symbol before 1985 and the current symbol.

of solid state materials eliminated the need for vacuum tubes and their power supplies. Solid state back to back rectifiers were both smaller and cheaper. The telephone company used these devices as surge protectors and as a way of eliminating load clicks on the telephone lines.

Fig. 1 shows the circuit diagram symbols for a varistor. The current symbol was adopted at the time when various types of diodes and transistors had different symbol. The early varistor symbol describes what a varistor does in a circuit.

There are a number of semiconductors that have been considered for use in varistors. The criteria used for selecting the varistor material are: the material band pass voltage, the degree of non-linearity of the varistor material, and the maximum safe operating temperature along with the heat absorption per unit volume. All three of these things are important for varistors used in electronics, commercial power systems, superconducting magnet quench protection systems.

If the band pass voltage is zero, the semiconductor is a conductor. If the band pass voltage is high, the semiconductor is an insulator. One would like to have a band pass voltage that is >1 eV. Si (silicon) has a band pass voltage of 1.14 eV, the most common form of SiC (silicon carbide) has a band pass voltage of 2.36 eV and ZnO (zinc oxide) has a band pass voltage of 3.37 eV. The actual forward voltage per junction within a varistor is less than the band pass voltage of the material as a whole. Most commercial varistors use Si, SiC or ZnO as the semi-conductor. Other materials are possible, but for various reasons they are not used commercially.

Fig. 2 illustrates the voltage versus current behavior of a typical zinc oxide varistor at a temperature of 298 K. Over six orders of magnitude of current, the varistor voltage is highly non-linear as a function of current. At high currents and very low currents the varistor behaves like a constant resistance resistor. Note, if $\alpha = 1$, the varistor would be a constant resistance resistor, but if the value of α is infinite, the varistor would be a perfect constant voltage resistor, which is not possible. Temperature has a definite effect on the low current end of the

This work was supported by the Office of Science U.S. Department of Energy under DOE Contract No. DE-AC-02-05CH11231. (Corresponding author: Michael A. Green.) Bruce P. Strauss is with the IEEE Council on Superconductivity, Potomac, MD 20854 USA (e-mail: bstrauss@alum.mit.edu). Michael A. Green is with Lawrence Berkeley Laboratory, Berkeley, CA 94720 USA (e-mail: magreen@lbl.gov).

Fig. 2. A Littelfuse Varistor V-I curve plotted on a log-log Scale [5].

curve shown in Fig. 2. The leakage current at 10 V increases two orders of magnitude when the temperature increases to 398 K, while at 100 V, the leakage current is almost unchanged [5]. This is certainly true for ZnO varistors. This is probably true of SiC varistors and Si diodes too. These authors don't have data for operating data for varistors at cryogenic temperatures, but one would expect the forward voltage to be higher at cryogenic temperatures.

Before talking about more specific about varistor materials, one should look at characterization of the non-linear behavior of the varistor. In the central varistor operation section of Fig. 2, I is proportional to V^α . One can look at this equation in another way as follows;

$$\frac{V(t)}{V_0} = \left[\frac{I(t)}{I_0} \right]^b \quad (1)$$

where V_0 is the voltage at the start of the quench protection; $V(t)$ is the voltage across the coil at time t after the varistor has been put across the coil; I_0 is the coil current when the varistor is switched at the start of quench protection and $I(t)$ is the coil current as a function of t after the varistor has been put across the coil. The value of $b = 1/\alpha$, which is more useful for calculating quench protection in superconducting magnets.

II. CHARACTERISTICS OF COMMERCIAL VARISTORS

A. Silicon Carbide Varistors

In the late 1930's Ronald W. Stillars (PhD from Oxford University in 1937) was studying silicon carbide as an insulator for electrical components while working for Metropolitan Vickers Ltd in Manchester U.K. (Metrosil). We have not found any early papers about his work. Metrosil was producing surge protectors and other such devices before and during World War II that were made from silicon carbide. There varistors were made from a sintered ceramic that was 90 to 95 percent silicon carbide [6]. The average grain size and the junction forward voltage determines the forward voltage across the varistor. The forward voltage across each junction is about 2 V (~85 percent of the

Fig. 3. A Metrosil high current silicon carbide varistor Pack [9].

band pass voltage). The forward voltage V_{VAR} of the silicon carbide varistor carrying a current of 1 A, with an active length of L , an average grain size d , and the grain boundary forward voltage Δ can be approximated with the following expression;

$$V_{VAR} \cong \Delta \left(\frac{L}{d} + 1 \right) \quad (2)$$

The value of b for the silicon carbide varistors was between 0.2 and 0.35, and $\Delta = \sim 2$ V. The Japanese came up with using aluminum or boron at the grain interfaces to decrease b to 0.12 to 0.17 [7]. Silicon carbide varistors can have a b as low as 0.09 [8]. An advantage of this kind of varistor is that they can operate at temperatures up to 185 °C for a short time.

Metrosil produces varistors for superconducting magnets quench protection made from fourteen SiC discs 160 mm in diameter that produce 800 V with currents as high as 16 kA for a short time [9] (see Fig. 3). The company sales engineer suggests that the value of b can be decreased by adding silicon and other things to the ceramic [10]. It is not known what the additions will do to the maximum operating temperature of the varistor. In 1977, the Lawrence Berkeley Laboratory used a silicon carbide varistor for superconducting magnet quench protection in combination with quench back from an 1100-O aluminum magnet mandrel [11], [12].

Table I compares the forward voltage Δ , the non-linearity coefficient b , thermal conductivity k , specific heat C , density ρ , the thermal expansion coefficient $\Delta L/L$, material yield stress σ , and the material Young's (elastic) modulus Y for silicon carbide, zinc oxide and silicon diodes.

B. Zinc Oxide Varistors

The first metal oxide varistors (MOV) were described by Matsuoka in 1971 [13]. Zinc oxide varistors are fabricated in the same way as silicon carbide varistors but with different materials in the ceramic [5], [6]. The powder used to fabricate the varistor is 97 mole percent ZnO, 1 mole percent Sb_2O_3 and a half mole percent Bi_2O_3 , CoO, MnO, Cr_2O_3 , and trace amounts of things

TABLE I
PROPERTIES OF VARISTOR MATERIALS

Parameter	SiC	ZnO	Si Diode
Δ (V)	~ 2	~ 3	0.7 to 0.9
b constant	0.18 to 0.32	0.02 to 0.04	~ 0.03
k (W m ⁻¹ K ⁻¹)	500	~ 850	149
C (J kg ⁻¹ K ⁻¹)	750	490	703
ρ (kg m ⁻³)	3100	5600	2330
$\Delta L/L$ (m/m K ⁻¹)	4.5×10^{-6}	4.75×10^{-6}	2.6×10^{-6}
σ (MPa)	~ 550	~ 115	~ 102
Y (GPa)	410	110	~ 80

like Pr_2O_3 . The exact formulation is determined by such things as conduction uniformity and energy absorption capability [14]. Nonlinearity inducers are Bi and Pr. Nonlinearity enhancers (to reduce b) are Sb, Co, Mn, and Cr. These materials may have more than one effect on the properties of a ZnO varistor. The value of Δ used in (2) is between 2.6 and 3 depending on the formulation.

The process of making the varistors is as follows: 1) The powders are weighed, mixed and then ground with a ball mill. 2) The power is dried and calcinated at 800 to 900 °C and pressed into the final shape before firing. 3) The ceramic is fused at temperatures between 1100 and 1400 °C. 4) After firing, the discs must be lapped prior to electroding to provide maximum contact between discs. 5) The electrodes are often plasma sprayed aluminum. 6) The edges of the discs can be insulated with glass or ceramics. 7) The final step is an anneal at 600 °C before the discs are assembled into a series parallel circuit with the desired voltage and current carrying capacity. A single stack of ZnO discs may look a lot like the stack of SiC discs in Fig. 3.

The real advantage of ZnO varistors is the value of b . In most cases $b = 0.02$ to 0.04 over a current range of five orders of magnitude. ZnO varistors can have $b = 0.01$ over a more limited current range. ZnO varistors are made in a number of countries. A manufacturer in the US is Littelfuse [15].

C. Using Diode Packs As Varistors

One should not ignore the fact that power diodes hooked up in series to form a varistor. Eleven hundred diodes, with a forward voltage of 0.7 V at 1 mA, in series could produce a voltage of ~ 1000 V at a current of 300 A. If one adds two more diodes to the diode pack, the diode pack would act like a varistor and have the same forward voltage in both directions. The b for silicon diodes is between 0.02 and 0.03. The two extra diodes must be able withstand a reverse voltage of a least two times the forward voltage of the varistor made from the diode stack. Diodes stack of this nature are commonly used as discharge circuits for magnets [16] Fig. 4 show a circuit of $N+2$ diodes that will act like a varistor that produces a varistor voltage 0.7–1.0 V with 1 mA flowing through the varistor. At higher currents the forward voltage increases as I^b .

Fig. 4. An array of N diodes that will produce a varistor forward voltage of $V_D (N-2)$ where V_D is the forward voltage of each diode and N is the total number of diodes that are in the varistor pack.

Fig. 5. The figure shows the quench protection integral F for Hastelloy C-276 (triangles) and $\text{RRR} = 100$ copper (squares) in an HTS conductor [19].

The number of diodes and the type diode used device shown in the Fig. 4 above depends on the energy rating for each of the diode shown above and the current $i(t)$ as a function of time t .

III. INTEGRAL OF $J^2 DT$ FOR SAFE MAGNET QUENCHING

Quench protection theory is based on using an adiabatic model that assumes little or no heat transfer from the quench zone [17], [18]. The burnout condition is determined by the maximum allowable coil hot-spot temperature T_{HS} . There is a function $F(T)$ for each material in the conductor as given by the following expression;

$$F(T_{HS}) = \int_0^{T_{HS}} \left[\frac{C(T)}{\rho(T)} \right] dT = \int_0^\infty J(t)^2 dt, \quad (3)$$

where $C(T)$ is the volume specific heat matrix material (either Cu or Hastelloy) and $\rho(T)$ is the electrical resistivity of the matrix material as a function of T . $J(t)$ is the current density in the conductor. Fig. 5 shows F for Hastelloy-22 and copper with an $\text{RRR} = 100$.

From Fig. 5, one can see that the quench protection integral is dominated by the copper in the conductor. In the normal state, Nb-Ti or Nb₃Sn has about the same hot spot temperature curve as the Hastelloy C-276 in an HTS conductor, because the normal state resistivity is the same within a factor of three. Pure silver in a conductor can be treated like copper. Thus, the effect of the normal superconductor or the Hastelloy on the total F is small compared to the conductor copper or silver.

For most superconductors the equation for the conductor F^* is as follows;

$$F^*(T_{HS}) = \frac{1}{f} [F(T_{HS})]_{Cu} \simeq \frac{1}{f} \int_0^\infty J(t)^2 dt, \quad (4)$$

where f is the fraction of copper in the conductor

IV. QUENCH PROTECTION OF A MAGNET THROUGH A RESISTOR OR A VARISTOR

Discharging a superconducting coil across a resistor produces an exponential current decay with a time constant τ , where $\tau_1 = L_1/R_1$. An exponential current decay can be integrated from time zero to infinity to yield an $F^*(T_{HS})$ at the end of the discharge, which is as follows;

$$F^*(T_{HS}) = \frac{L_1}{\Gamma R_1(0)} \frac{1}{f} J(0)^2, \quad (5)$$

where $\Gamma = 2$ for a constant resistance resistor and $\Gamma = 3$ for a varistor [12]. $R_1(0)$ is the resistance at the current when $t = 0$. A varistor is not a perfect constant voltage resistor, but it can reduce the $F^*(T_{HS})$ by about a third.

There is a discharge minimum starting voltage for safe quenching even when there is no coil quench propagation. This starting voltage is given as follows;

$$V_0 = \frac{I_0 L_1}{\Gamma F(T_{HS})^*} \frac{1}{f} J_0^2, \quad (6)$$

where V_0 is the discharge voltage at $t = 0$ when the switch is open; J_0 is the conductor current density at $t = 0$; I_0 is the coil current; L_1 is magnet self-inductance; and $F(T_{HS})^*$ is defined by (3). The discharge voltage in (6) assumes the quench is detected at $t = 0$. If the quench is not detected quickly, the value of F^* must go up, so the discharge voltage also goes up. In 1991 the Japanese showed that a ZnO varistor reduces the integral of $J^2 dt$ by about one third compared to a conventional resistor that puts the same initial voltage across the coil [20].

V. QUENCH PROTECTION WITH A RESISTOR OR A VARISTOR IN A MAGNET WITH A SHORTED SECONDARY

In order to have a viable quench protection system for large coils with high conductor current density, one must reduce the coil current rapidly after quench detection. The energy that is removed from the coil can be used to speed up the quench through quench-back [21]. Ideally the two processes should occur simultaneously. Having a well-coupled high RRR shorted-secondary will cause the current to shift from the coil to the secondary. This process was used to protect high current density LTS magnets at LBL during the 1970's [11], [22]. Maddock and James [23] contended that having a separate secondary was counter-productive in magnets that were cryogenically stable, but in magnets with high current density coils that were closely coupled to the secondary, the current in the coils could be reduced rapidly, which means that the conductor burnout takes a longer time.

Figure 6 shows a simple coupled circuit where a resistance R_1 can be put across the superconducting coil with a self-inductance

Fig. 6. The magnet coil is shown with a resistor across it. The secondary circuit or mandrel shown as inductively coupled with magnet coil [24].

L_1 . The shorted secondary has a resistance R_2 and a self-inductance L_2 . If the time constant $\tau_1 = L_1/R_1$ is significantly shorter than the time constant $\tau_2 = L_2/R_2$, most of the coil current is shifted from the coil to the secondary. The time constant for current shift from the primary to the secondary τ_S (the short time constant) is a function of how well the primary and the secondary are inductively coupled. If the coil and the secondary circuits are close together compared to their radii, the coil coupling coefficient is ~ 1 . As the coupling coefficient approaches 1, the long time-constant $\tau_L = (\tau_1 + \tau_2)$. The short time-constant τ_S can be calculated as follows;

$$\tau_S = \frac{\varepsilon \tau_2 \tau_1}{\tau_1 + \tau_2}, \quad \text{where} \quad (7a)$$

$$\varepsilon \approx \left[1 - \frac{M_{1-2}^2}{L_1 L_2} \right], \quad (7b)$$

with M_{1-2} the mutual-inductance between the coil and the shorted secondary circuit. $F^*(T_{HS})$ at the end of the discharge takes the following form when the resistances R_1 and R_2 are constant with time [15];

$$F^*(T_{HS}) = \frac{1}{f} J(0)^2 \left[\frac{\tau_1^2}{2(\tau_1 + \tau_2)} + \frac{\tau_S}{2} \right]. \quad (8)$$

When one compares (8) with (5), the equation with the shorted secondary will yield a lower $F^*[T_{HS}]$.

When a varistor is used in place of a resistor, the game changes when there are shorted secondary circuits. The varistor in the primary reduces the magnet current depending on the coupling factor ε and b . When ε is small, the current in the coil is reduced an order of magnitude or more compared to a resistor that produces the same initial voltage across the coil [19], [24]. When b is small, the varistor pushes the primary current down and keeps it down for longer time. This was demonstrated at LBL in 1977 on a high current density magnet that had a stored energy of 2 MJ [11], [12].

The following expression can be used to estimate the energy absorbed by a quench protection varistor;

$$\int_{T_0}^{T_M} C(T) dT \simeq \int_0^\infty E(t) J(t) dt, \quad \text{or for a single varistor,} \quad (9a)$$

$$A_V L_V \int_{T_0}^{T_M} C(T) dT \simeq \int_0^\infty V(t) I(t) dt, \quad (9b)$$

where $C(T)$ is the volume specific heat as a function of T , $E(t)$ is the varistor electric field as a function of t , $J(t)$ is the varistor current density as a function of time t , L_v is the varistor length, A_v is varistor area, $V(t)$ is the varistor voltage as a function of t , and $I(t)$ is the varistor current as a function of t . The heating of the of the varistor is proportional to the integral of $J^2 dt$ at the hot spot in the superconducting coil. A varistor that reduces the integral of $J^2 dt$ in the coil hot spot can be made smaller the magnet has a coupled shorted secondary circuit.

VI. COLCUSION

Diodes have a low forward voltage with current going through the diode in the forward direction, but it has a much higher voltage when current flows through the diode in the backward direction. Conceptually a varistor behaves like a pair of diodes hooked in parallel that have the same voltage when the current goes through it in both directions. Many diodes can form a varistor pack. Ideally, a varistor is nearly a constant voltage device. At very low currents or very high currents varistors behave like resistors. Most varistors are either made from SiC or ZnO. ZnO varistors are closer to a constant voltage device than are SiC varistors. SiC varistors operate over a wider temperature range than ZnO varistors.

Either type of varistor when used in place of resistor will reduce the integral of $j^2 dt$ in the superconducting coil by about one third. With that reduction, the coil hotspot temperature is reduced. When the coil is well coupled with a secondary circuit (or circuits), the change in the integral $j^2 dt$ can change greatly along with the hot spot temperature. The reduction greatly depends on ε and b [11], [19], [24]. For both types of varistors the energy deposited in the varistor material is shown in (9a) and (9b). A well coupled secondary circuit greatly reduces the coil hot-spot temperature and the varistor size.

REFERENCES

- [1] S. Millman Ed., *A History and Science of the Bell System, Physical Science (1925 to 1980)*. NJ, USA: AT & T Bell Laboratories, p. 413, 1983.
- [2] F. Braun, "Über die stromleitung durch schwetelmetalle (On current conduction in meltal sulfides)," *Annelden der Physik und Chemie*, vol. 153, pp. 556–563, 1874.
- [3] T. K. Sarkar, *History of Wireless*, vol. 94. Hoboken, NJ, USA: Wiley, 2010, pp. 291–308.
- [4] L. O. Grovdahl and P. H. Geiger, "A new electronic rectifier," *J. AIEE*, vol. 46, no. 3, pp. 357–366, 1927.
- [5] "Littelfuse varistors, basic properties terminology and theory," in *Application Note AN9767.1*. Chicago, IL, USA: Littelfuse Corporation, [Online]. Available: www.littelfuse.com
- [6] C. J. Frosch, Bell Telephone Laboratory, Summit NJ, "Manufacture of silicon carbide varistors," U.S. Patent 2807856, 1957.
- [7] T. Masuyama *et al.*, Matsushima Electric, Osaka Japan, "Silicon carbide varistors," U.S. Patent 3380936, 1965.
- [8] F. A. Modine and H. M. Hyatt, "New varistor material (a SiC varistor with $b < 0.1$)," *J. Appl. Phys.*, vol. 64, 1988, Art no. 4229.
- [9] M & I Material Ltd (Metrosil). Varistor Data Sheets for an 800 V varistor that can carry up to 16 kA, Trafford Park, Manchester, U.K., 2018. [Online]. Available: www.materials.com
- [10] Private communication with a Metrosil sales representative presented at the Cryogenic Eng. Conf. Int. Cryo. Mater. Conf., Hartford CT, USA, Jul. 2019.
- [11] P. H. Eberhard *et al.*, "Quenches in large superconducting magnets," in *Proc. 6th Int. Conf. Magnet Technol. MT-6*, 1977, pp. 654–661.
- [12] J. D. Taylor *et al.*, "Quench protection in a 2 MJ magnet," *IEEE Trans. Mag.*, vol. MAG-15, no. 1, pp. 855–859, Jan. 1979.
- [13] M. Matsuoka, "Nonohmic properties of zinc oxide ceramics," *Japanese J. Appl. Phys.*, vol. 10, no. 6, pp. 736–746, 1971.
- [14] L. M. Levinson and J. R. Phillips, *Zinc Oxide Varistors-A Review*. American Ceramic Society Bulletin, Apr. 1986.
- [15] Littelfuse Corporation. Chicago, IL USA, pp. 628–1000, [Online]. Available: www.littelfuse.com
- [16] M. A. Green *et al.*, "Slow current discharges and quenching of the MSU superconducting cyclotron Gas-stopper magnet," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 4702405.
- [17] W. H. Cherry and J. T. Gittleman, "Thermal and electrodynamic aspects of the conductive transition process," *Solid State Electron.*, vol. 1, no. 4, pp. 287–305, 1960.
- [18] M. N. Wilson, *Superconducting Magnets*. Oxford U.K.: Oxford Univ. Press, 1983, pp. 200–232, Ch. 9.
- [19] M. A. Green and X. L. Guo, "Protection of large insulated react and wind HTS solenoids and toroidal coils," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, Aug. 2019, Art. no. 4702507.
- [20] T. Ishogohka and Y. Kushiro, "Quench protection of a superconducting magnet using a ZnO arrester," *Cryogenics*, vol. 31, no. 7, pp. 562–565, 1991.
- [21] M. A. Green, "Quench back in thin superconducting solenoid magnets," *Cryogenics*, vol. 24, pp. 3–10, Jan. 1984.
- [22] P. H. Eberhard *et al.*, "Quench protection for superconducting solenoids with a conducting bore tube," Lawrence Berkeley Laboratory Report LBL-6444, UC-38, TID-4500-R65, May 1977.
- [23] B. J. Maddock and G. B. James, "Protection and stabilization of large superconducting coils," *Proc. IEE*, vol. 115, no. 4, pp. 543–547, 1968.
- [24] M. A. Green, "The effect of shorted secondary material on quench protection of an HTS tape solenoid discharged across a varistor," in *Proc. IOP Conf. Ser. Mater. Sci. Eng.*, 2020, vol. 755, Art. no. 012127.