Chapter 1

ZnO based Varistor Ceramics - An Introduction

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1.1. ZnO based Varistor

Zinc oxide varistors are semiconductor ceramic device, whose nonlinear electrical properties make them competent to sense and limit transient surges repeatedly and quickly, protecting semi-conductive devices and as a surge-arrestors in power system from being destroyed [Matsuoka et al. (1969)]. Surge arresters are widely applied on distribution networks to protect switches and transformers against lightning and switching surges [Eda et. al (1980); Levinson et. al (1986)]. ZnO varistors have become one of the most useful protecting devices and are very important devices in transient surge suppression technology. ZnO varistors are applicable as characteristics elements in gapless-type lightning arresters used in electric power systems. Moreover, automotive use has also been by the improvements of the characteristics for high operating temperature and low operating voltages [Gupta et. al (1979); Wong et al. (1980); Alles et. al (1993)]. At low voltage, varistors act as resistors, however they become conductors at high voltage. To protect components from high voltage transients, these varistors are used in parallel with circuits as shown in Fig. 1.1. In normal situations, a small current is passed from the power supply. However there may be a large current in abnormal situations and varistor draws the current to ground.

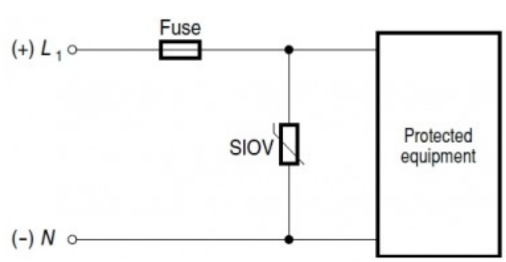

Figure 1.1: Parallel connection of varistor to a circuit [Gupta et. al (1979)]

Later, ZnO varistors were extensively used as surge arresters for protection of series compensation and HVDC converter stations. The equipment used in SC or

HVDC stations, e.g. capacitors, reactors, transformers, filters or valves, are exposed to overvoltages of different origin. Lightning strokes into the electric power system, the station itself or into its vicinity lead to lightning overvoltages. Switching action within the system including the periodic switching of the HVDC converter valves causes switching overvoltages. Certain operating conditions due to load flow control cause temporary overvoltages. Finally, overvoltages may be caused by internal or external faults and subsequent short circuit current. Without counter measures, occurrence of these overvoltages in the system can lead to breakdown of the equipment insulation and its failure. In order to protect the equipment from overvoltages, surge arresters are used within the system. The purpose is to always limit the voltage across the terminals of the equipment to be protected below its insulation withstand voltage. This is achieved by connecting elements with an extremely non linear voltage current characteristic in parallel to the terminals of the equipment. So called metal oxide (MO) surge arresters containing ceramic bodies mainly made from zinc oxide (ZnO) and bismuth oxide are used nowadays [Diseko (1990)].

1.2. Background

The first transient voltage surge suppressors (TVSS) were **selenium rectifiers** that were employed to protect telephone systems in the early 20th century [Gupta et. al (1992)]. By 1930, the **first varistor ceramics** were developed by **Bell Systems** in which sintered compacts of **silicon carbide** (SiC) particles were the materials used to make varistors. And for low-voltage applications, the TVSS devices used in the 1930s were single crystal silicon devices, namely avalanche or **Zener diodes** [Matsuoka et al. (1969)]. After the Second World War, technological improvements have been done on TVSS especially in the decades of 1960 and 1970. The United States and Japan were leading the world in research and development activities on varistors since then until now. By 1969, the first varistor ceramics based on **zinc oxide** material were developed by **Matsuoka**. He unleashed significant scientific discoveries of ZnO varistors which include the roles of additives or substitutional ions, Bi_2O_3-rich liquid phase at grain boundaries and the enhancement of the degree of nonlinearity by manganese and cobalt dopants. Astonished by Matsuoka's findings, General Electric Corporation and Matshushita Corporation formed an alliance in research and development to further pursue the science and technology of ZnO varistors and a few years after the joint venture. So many research publications were made on ZnO varistors. Concurrently, new ZnO varistor products were developed and they were found to be far superior to SiC-based varistors in terms of these application properties: The general features of the gapless varistors include polycrystalline microstructures, highly symmetrical nonlinear current–voltage (I–V) behavior with respect to bidirectional polarity, low leakage current at maximum continuous operating voltage, large current range for a narrow voltage increase yielding excellent voltage ratio in the nonlinear region, fast response to the rising surge voltage, low standby power, no follow-on current, high stabilization at surges, large energy- handling capability, and high absorption for transient voltages. These features allowed varistor applications in the power systems protection, suppression of internally generated spikes in electronic circuits, relay and electromagnetic valve surge absorption, surge protection of other devices involving integrated circuit, diode, transistor, thyristor, triac, etc. for consumer, industrial, automobile, controller electronics, telephone and telecommunication systems appliances.

1.3. Varistor Microstructure

Before proceeding to a description of the electrical characteristics of metal oxide varistors, we briefly describe the ceramic microstructure of this material. The microstructure of a varistor plays a key role in the nonlinear properties. The electrical characteristics are defined by microstructure development and the inter relationship between microstructure, the chemistry and the physics of the varistor. The microstructure can be manipulated by controlling the processing conditions and using various dopants. A highly schematic block diagram of the varistor microstructure is shown in Fig. 1.2. The device consists of conducting

ZnO grains, size d, surrounded by a thin insulating oxide layer of thickness t. When a current is applied, an electrical current is passed through the grains. The shortest electrical pathway is the route that has the least number of grains between the electrodes. The varistor action is correlated with processes occurring at a ZnO-ZnO grain boundary [Levinson et al. (1975)]. From the block model, it can be noted that the electrical characteristics of ZnO varistors are related to the bulk material. The device is inherently multi-junction with varistor action shared between the various ZnO grain boundaries. For the important nonlinear parameter e.g. breakdown voltage (V_B) it means that fabricating a varistor with appropriate number of grains (n) in series between the electrodes is possible. The processes to achieving are varying device thickness with fixed grain size or changing the grain sizes with fixed device thickness. These can be explained in Equation 1.1.

$$\mathbf{V_B = nV_g = \frac{D}{d} V_g} \tag{1.1}$$

Where V_g is the breakdown voltage per intergranular barrier

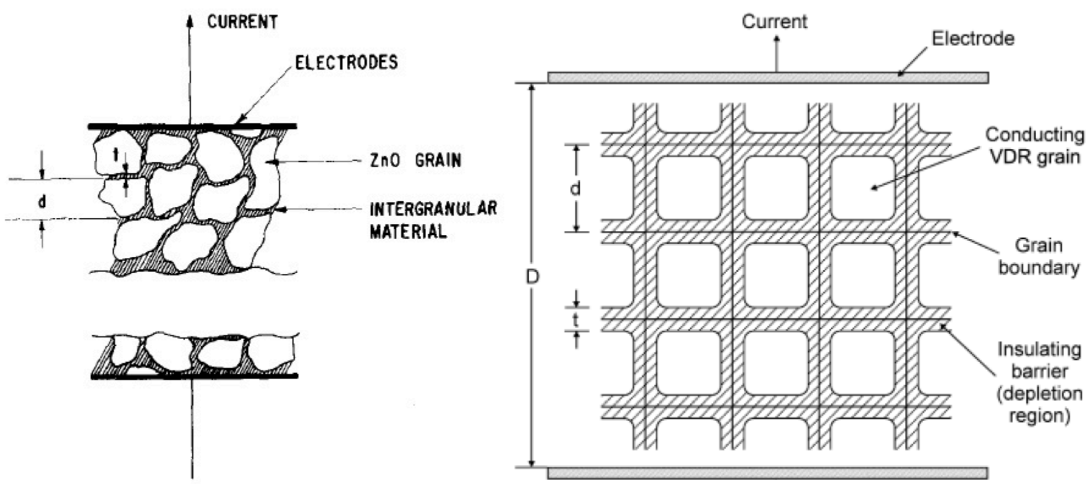

Figure 1.2: Schematic depiction of the microstructure [Levinson (1975)], and block model of ZnO varistor. Electrodes are attached and current flows as indicated. [Bueno (2008)].

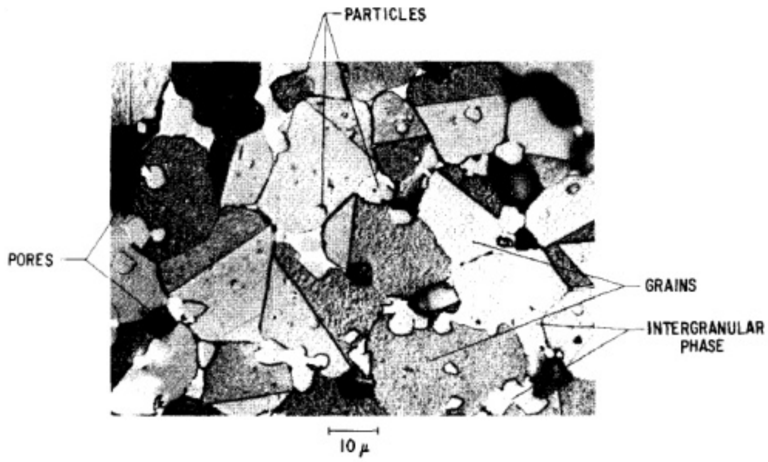

Figure 1.3: Photomicrographs of polished and etched varistor sample [Levinson (1975)]

The actual microstructure of a metal oxide varistor is considerably more complex than the somewhat idealized depiction of Fig. 1.2. Fig. 1.3 depicts photomicrographs of polished and etched varistor sample. Three phases; (1) grains, (2) intergranular material and (3) particles are evident. In addition, some porosity can be also seen. The "grains" are the predominant phase in these varistors and consist of relatively small conducting ZnO crystals. The straight lines evident in some of the ZnO grains presumably correspond to twin boundaries delineating different ZnO crystal planes having different etch properties. The whitish areas lying largely between the ZnO phases have been labeled "intergranular material". However, the true intergranular interface, which controls the varistor action is believed to be extremely thin (-100A°) and is either highly microcrystalline or amorphous in varistors [Levinson et al. (1975)]. The intergranular material in Fig. 1.3 corresponds to fairly well-crystallized agglomerates of excess intergranular phase structural determinations [Wong et al. (1974)] upon these agglomerates indicated the material to be a bismuth oxide rich pyrochlore. In addition to the ZnO grains and the intergranular material, a third phase labeled "particles" is evident in Fig. 1.3. X-ray studies [Wong et al. (1974)] have demonstrated this phase to have a spinel-type structure with the approximate formula $Zn_7Sb_2O_{12}$. The spinel particles are insulating and play only a secondary role in determining the device properties. From micrographs of the type given in Fig. 1.2 determine the mean grain size ‘d’ of the ZnO grains in the varistor to be about to ≈ 25μm. Remark that the breakdown field in varistors is around to 1-10 KV/cm, the breakdown voltage V_b per intergranular barrier to be around to ≈ 1-2.5V/barrier [Levinson et al. (1975)]. This value may be also reported by Matsuoka (1971), who finds ZnO grain sizes some tens of microns and breakdown voltages V_b per barrier of the order of volts. This similarity is important, since it implies that qualitatively similar varistor action is obtained for a broad range of ZnO plus insulating oxide mixes. Indeed, Matsuoka et al. (1970) have disclosed a large number of compositions, which produce useful ZnO-based varistors. Thus any theory describing the device conduction mechanism should be generally applicable to a wide variety of insulating oxide inter granular materials and thus should be insensitive to certain extrinsic details of the insulating barrier such as trap density, impurity content Fermi level position etc [Levinson et al. (1975)].

1.4. Conduction Mechanism

The conduction mechanism in ZnO varistors is not fully understood even though many models have been proposed. In the continuation, eight models have been proposed as shown in Table 1.1.

(1) The first model was the theory of space charge limited current (SCLC) proposed by Matsuoka (1971). The concept of the model is segregation layer consisted of many different oxides and was assumed to contain many traps.

(2) The second model was tunnelling through a thin layer at the grain boundaries by Levinson and Philipp (1975).

(3) The third model was tunnelling through Schottky barriers proposed by many groups. First model did not take the account to consider the heterojunction [Levine (1975), Bernasconi (1977), Hower (1979)]. For example in model proposed by Morris (1976), the conduction mechanism showed the electron tunnelling and hopping in the intergranular layers of amorphous Bi_2O_3-ZnO. Two main factors supporting this mechanism, first is slight reduction in both the polarisability and AC resistivity with frequency and second the low activation

energy. The other model took into consideration the heterojunctions [Emtage (1977), Eda et al. (1978)]. In model proposed by Emtage et al. (1977), the conduction mechanism is based on the grain boundary. The main evidence supporting this model is the large apparent permittivity obtained for the varistors (~1000 ε_0) where ε_0 is the permittivity of free space (8.854×10^{-12} F m^{-1}). This value is larger than that of either the ZnO grains (10 ε_0) or the intergranular layer (16 ε_0). In addition, Eda (1978) suggested that there is a semiconductor-insulator-semiconductor (SIS) structure at the grain boundary. Therefore SIS composed of the intergranular layer (insulator) sandwiched between two schottky barriers formed at ZnO grain surfaces. Moreover the thickness of the intergranular layer was reportedly less than 500 Å, much thinner than that reported by Matsuoka (1971).

(4) The fourth model was tunnelling through homojunctions of ZnO [Einzinger (1978)]. Regarding the theory, thermal equilibrium of defects which are formed during cooling at the grain boundaries is important.

(5) The fifth model was tunnelling through schottky barrier with the hole creation [Mahan et al. (1979)]. This model proposed the importance of minority carriers (holes) at the grain boundaries.

(6) The sixth model was the bypass effect at heterojunctions. This model represents the vital role of Bi_2O_3-rich intergranular layer in the small current region and assumed that parallel current paths through the heterojunctions and the Bi-rich intergranular layers should be considered.

(7) The seventh model was hole induced breakdown [Pike (1974), Blatter et al. (1986)]. The model demonstrated that the highly nonohmic property is caused by the lowering of the potential barriers at the grain boundaries because of the hole accumulation. The holes were formed by accelerated electrons in the depletion region. The dependence of potential barriers on the interface states and or the bulk traps was proposed [Blatter et al. (1986)].

(8) The eighth model was induced space charge current at the heterojunction composed of thin films of ZnO and Bi_2O_3 [Suzuoki et al. (1987)].

Table 1.1 Timeline of the proposed conduction model in ZnO varistor [after Eda (1989)].

Year	**Researchers**	**Model**
1971	Matsuoka	Space charge limited current
1975	Levinson and Philipp	Tunnelling through a thin layer
	Levine	Tunnelling through Schottky barrier
1976	Morris, Bernasconi et al.	Tunnelling through Schottky barrier
1977	Emtage	Tunnelling through schottky barrier with heterojunction
1978	Eda	Tunnelling through schottky barrier with heterojunction
	Einzinger	Tunnelling through heterojunction
1979	Hower and Gupta	Tunnelling through schottky barrier
	Mahan	Hole assisted tunnelling through schottky barriers
1982	Eda	Bypass effect at heterojunctions
1984	Pike	Hole induced breakdown
1986	Levinson and Philipp	Bypass effect at heterojunctions
	Blatter and Greuter	Hole induced breakdown
1987	Suzuoki et al.	Space charge induced current

Even though many conduction mechanisms have been proposed, the back-to-back double schottky barrier model has been widely accepted by many studies. It has been used to interpret the various electrical properties of ZnO varistors.

1.5. Effect of Additives Oxides

Since the invention of ZnO varistors, most of the developments and investigations have been based on the ZnO-Bi_2O_3 system because of its simplicity and efficiency. However, the nonlinearity of the ZnO-Bi_2O_3 binary system did not show the most effective results as the nonlinear coefficient was less than 10 [M. Matsuoka (1969)]. So that additives plays an important role for ZnO varistors because they can improve the nonlinearity. Metal oxide additives affect various properties of ZnO varistors. For instance, cobalt and manganese enhance the nonlinear characteristics. This M^{2+} ion goes into a solution in ZnO. Furthermore, it is believed that the transition metal oxides are involved in the formation of interfacial states and deep bulk traps, both of which contribute to highly nonohmic behaviour. The addition of titanium, aluminium and antimony retards the grain growth; on the other hand, silicon increases grain growth. Antimony forms the spinel phase and a pyrochlore phase blocking grain growth. Moreover Sb promotes the formation of twins in ZnO grains and improve the nonlinearity. Thus the I-V characteristics become better stabilised against electrical stresses and the breakdown voltage increases. The role of Sb_2O_3 were proposed as: (i) grain growth suppression and (ii) the solubility enhancement of ions such as Zn in the Bi_2O_3-rich liquid phase [K. Eda (1989)]. The later role is very important in order to control the defect distribution at the grain boundaries during the cooling. To improve the reliability, NiO, Cr_2O_3, or a small amount of glass frit are used. These additives stabilise the intergranular layer against the electric load and ambient conditions e.g. temperature and humidity. Table 1.2 shows roles of additives in ZnO varistors. Furthermore, some metal-oxide additives are specific to grains and/or grain boundaries. For example, Gupta (1992) studied the effect of the additive-induced defect on grain, grain boundaries or both when the additives were sodium and aluminum. It can be noted that aluminium addition is both grain and grain boundary specific, whereas the addition of sodium is only grain boundary specific [Gupta (1992)].

Table 1.2 Roles of additives in ZnO varistors [after K. Eda (1989)]

Roles	**Additives**
Isolation among ZnO grains and supplying required elements to grain boundaries (O_2, Co, Mn, Zn, etc.)	Bi, Pr > Ba, Sr, Pb, U
Improvement of non-ohmic exponent formation of interface states	Co, Mn > (Sb)
Improvement of stability	Sb, glass, Ag, B > Ni, Cr
Improvement of non-ohmic exponent in a high current region - formation of donors in ZnO	Al, Ga > F, Cr
Grain growth suppression	Sb, Si
Grain growth promotion	Be > Ti > Sn

In Table 1-2, the approximate degree of effectiveness of the additives is roughly indicated by the symbol >.

1.6. Electrical Measurements

In this section, we represent results of both DC and AC electrical measurements on commercial varistors. Preliminary, we define the parameters relevant to the discussion of the electrical characteristics of varistors. In Fig. 1.4, we represent the metal oxide varistor by a simple equivalent circuit. The quantities P_p and C_{OBS} are associated with the intergranular layer and r corresponds to the series resistance of the ZnO grains. These values are in general functions of the field F and the measurement frequency ω. The magnitude of r is quite small and therefore important only at very high current levels where it is responsible for the "upturn" in the current-field characteristics (see Fig.1.4). In present study, its influence has been neglected. The equivalent circuit therefore consists of a capacitor C_{OBS} and a parallel resistance of resistivity P_p associated with the intergranular material. The field and frequency dependent quantity $p_p(F, w)$ is defined by $P_p \approx F/J$, where J is in phase current density. At very low field, Pp is independent of F, i.e., the varistor behaves in an Ohmic fashion.

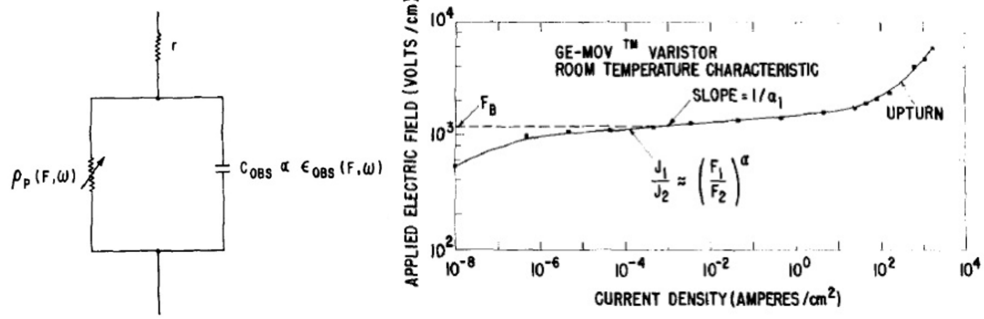

Figure 1.4: Simplified equivalent circuit for varistors and current density versus applied field for a typical varistor.

Fig. 1.4 shows the dc current-density vs field relation of a typical varistor. (At high current levels the data are obtained by a pulse technique to avoid heating the device. However the characteristic is essentially independent of pulse width.) The data are presented on a log-log scale. Traditionally the varistor characteristic has been represented by a relation of the form

$$J = (F/K)^{\alpha}, \qquad (1.2)$$

where K is a constant and α is the exponent indicating the degree of nonlinearity. The inverse slope of the curve at any given current density determines the corresponding value of α. On a plot of this nature, a horizontal straight line ($\alpha = \infty$) corresponds to a "perfect varistor", with the breakdown field F_B, constant for any value of the current density. For any real device, there is clearly some arbitrariness in the choice of F_B. We shall take it as the field where J = 1 mA/cm^2 From Fig. 5, we note that while α is fairly constant over a limited range of current, a given varistor is not characterized by a unique α. Eq. (1) is a fair representation of the correct relation, especially for high α. We also note at this juncture that K has units which depend on α and that the interpretation of Eq. (1) requires some care. A mathematically and physically more transparent version of Eq. (1) is given by

$$J_1/ J_2 = (F_1/ F_2)^{\alpha}, \qquad (1.3)$$

where J_1 and J_2 are the current densities corresponding to applied fields F_l and F_2 respectively and α is some average value within the range of $J_1<J<J_2$.

1.7. Selection Procedure

1.7.1. Overvoltage types and sources

Overvoltages are distinguished according to their originating point.

(a) Internal overvoltages: Internal overvoltages are those overvoltages that originate in the actual system which is to be protected, e. g. through

1. Inductive load switching
2. Arcing
3. Direct coupling with higher voltage potential
4. Mutual inductive or capacitive interference between circuits
5. Electrostatic charge
6. ESD.

With internal overvoltages, the worst-case conditions can often be calculated or traced by a test circuit. This enables the choice of overvoltage protective devices to be optimized.

(b) External overvoltages: External overvoltages are those overvoltages that affect the system which is to be protected from the outside, e. g. as a result of

1. Line interference
2. Strong electromagnetic fields
3. Lightning

In most cases the waveform, amplitude and frequency of occurrence of these transients are not known or if so, only very vaguely. And this, of course, makes it difficult to design the appropriate protective circuitry. There have been attempts to define the overvoltage vulnerability of typical supply systems (e. g. industrial, municipal, rural) so that the best possible protective device could be chosen for the purpose. But the scale of local differences makes such an approach subject to uncertainty. So, that for reliable protection against transients, a certain degree of “overdesign” must be considered. Therefore the following figures for overvoltage in 230 V power lines can only be taken as rough guidelines:

1. Amplitude up to 6 Kv
2. Pulse duration 0.1µs to 1 ms

Where varistors are operated directly on the line (i. e. without series resistor) normally the type series should be chosen. In systems with high exposure to transients (industrial, mountain locations) block varistors are to be preferred.

1.7.2. Principle of protection and characteristic impedance

The principle of overvoltage protection by varistors is based on the series connection of voltage independent and voltage-dependent resistance. Uses made of the fact that every real voltage source and thus every transient have voltage-independent source impedance greater than zero. This voltage independent impedance Z_{source} shown in figure 1.5 can be the ohmic resistance of a cable or the inductive reactance of a coil or the complex characteristic impedance of a transmission line. If a transient occurs, current flows across Z_{source} and the varistor that, because $V_{source} = Z_{source} \cdot I$, causes a proportional voltage drop across the voltage-independent impedance. In contrast, the voltage drop across the ZnO is almost independent of the current that flows.

$$V_{ZnO} = \left(\frac{Z_{ZnO}}{Z_{ZnO}+Z_{source}} \right) v \qquad (1.4)$$

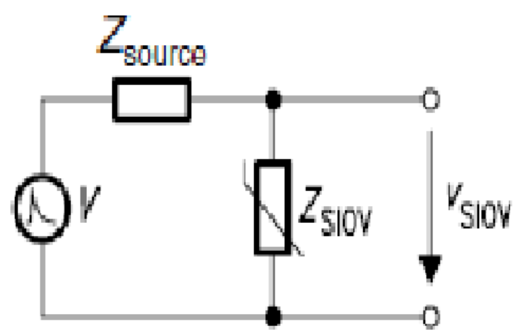

Figure 1.5: Equivalent circuits in which Z_{source} symbolizes the voltage-independent source impedance [www.epcos.com]

The intersection of the "load line" of the overvoltage with the V/I characteristic curve of the varistor is the "operating point" of the overvoltage protection, i. e. surge current amplitude and protection level. The overvoltage (1) is clamped (2) by a varistor (Fig 1.6)

V_B - Operating voltage

V_S - Superimposed surge voltage

For selection of the most suitable protective element, one has to know the surge current waveform that goes with the transient. This is often and mistakenly calculated by way of the (very small) source impedance of the line at line frequency. This leads to current amplitudes of unrealistic proportions.

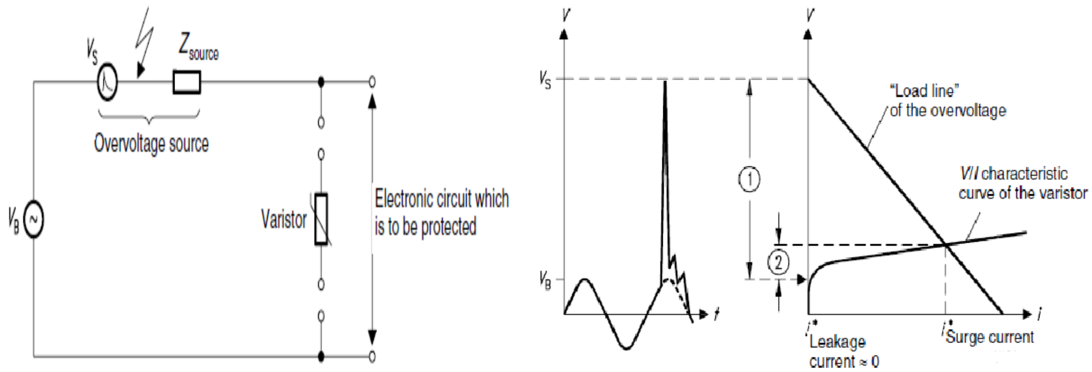

Figure 1.6: Principle of overvoltage protection by varistors [www.epcos.com]

Here, one has to remember that typical surge current waves contain a large portion of frequencies in the kHz and MHz range, at which the relatively high characteristic impedance of cables, leads etc. determines the voltage/current ratio [EPCOS Data Book (2008)].

1.8. Evolution of Overvoltage Protection Practice

The evolution of surge arrester technology has been characterized by both the gradual improvement of the various arrester components and more importantly by four successive major steps: the simple spark gap, the valve-type arrester, the introduction of active gaps and the gapless metal oxide arrester. The later is associated with ZnO varistors and the two former arresters were made with SiC resistors. The introduction of each arrester had an important impact on protection levels and cost of the power system equipment as a whole.

1.8.1. Simple spark gaps

During the first half of the twentieth century, protection of apparatus in electrical power systems was provided by rod gaps (also referred to as coordinating gaps) and a very high withstand voltage for the insulation [Standler (1989)]. The advantage of rod gaps lies in their simplicity and cost. However, they cannot support any voltage during their operation and cannot clear the power frequency follow current, which means that after sparking over a permanent fault occurs which leads to interruption of supply. Moreover, the time lag to sparkover and the dependence of sparkover on many factors may result in failure of the protective system. The combination of a high protective level with spark gaps still finds application today in low voltage applications but at high service voltages increasing the withstand voltage of insulation has a marked influence on costs. At 33 kV systems and lower, it is not recommended to use simple rod gaps because they may be bridged by birds; instead duplex gaps and/or triggered gaps of expulsion type may be employed.

1.8.2. Valve-type arresters

The discovery of the non-linear properties of silicon carbide (SiC) around 1930 made feasible the introduction of valve-type surge arresters to protect power systems against atmospheric discharges. The general design of a conventional arrester consists of plate-type gaps spaced by insulating rings with series non-linear SiC resistors also known as thyrite. The spark gap performs the switching function and the SiC resistor limits the follow current and enables the arrester to reseal. By subdividing the spark gap, it is possible to reseal at higher voltages eliminating steady state energy dissipation. Compared with spark gaps, valve-type arresters have a number of advantages but the protective level remains relatively high. The SiC elements have severe specification standards because most of the voltage is supported by the non-linear resistors and the arc voltage is comparatively negligible; also most of the energy associated with the discharge of a transmission line or cable is absorbed by the SiC non-linear resistors.

1.8.3. Surge arresters with active gaps

A significant improvement of arresters to alleviate problems of utilization was achieved by the introduction of active gaps (also called current-limiting gaps) [Muench, F.J (1990)]. These are characterized by the presence of blast coils that produce a strong magnetic field during the passage of arrester follow current.

The arcs across the individual gaps are then elongated and blown towards the edge of the chamber, thus producing an increased voltage drop during the follow current period. The power frequency voltage across the series non-linear resistors is therefore reduced with the consequent reduction of the follow current. The arc voltage opposes the follow current and interrupts it before the working voltage reaches zero. A further component of the active design is the grading system which ensures that the voltage is distributed uniformly between the series spark gaps.

Compared with simple gap arresters, active gap arresters have the following advantages:

(i) Arc voltage is of the order of the voltage drop across the non-linear SiC resistor

(ii) Protective level is substantially lowered

(iii) The energy absorbed by the resistors decreases; some of it is absorbed by the elongated arc and the other part remains in the transmission line because the follow current is interrupted before voltage zero.

(iv) Constant voltage during flow of arrester current

(v) The roots of the arc move along the electrode which reduces the change in arcing found in simple plate gap arresters.

1.8.4. Metal oxide surge arresters

The relatively high protective levels provided by SiC arresters became more and more economical disadvantage with the increase of maximum system voltages. In order to reduce the insulation levels of the apparatus, it was therefore necessary to try to reduce the protection levels of the surge arresters. Furthermore, the increase of transmission line lengths resulting increase of the energy that the arrester had to absorb in case of a line discharge through it. The search for new materials to obtain superior non-linear I–V characteristics led to the discovery of zinc oxide (ZnO) varistors in the late 1960s. The impedance of ZnO varistors at voltages below the rated voltage is so high resulting the current is in the milliampere range. The direct consequence of this low current consumption was the possibility of constructing surge arresters with no series gaps. The first power system gapless metal oxide surge arresters were completed in the mid 1970s [Lat (1981), Shih et. al (1985)]. The absence of the gaps and the extreme non-linearity of the voltage–current characteristic of the material resulted in the following additional changes in the main features of arrester protection:

(i) Elimination of grading resistors or capacitors, which reduced further the number of parts used for the arrester construction.

(ii) Energy absorbed by the non-linear resistor represents only a fraction of the discharge energy of the transmission line because there is no follow current, and parallel connections of varistors to increase the energy absorption capability of the arrester are now possible [Kershaw et. al (1989)].

(iii) Lower discharge voltage (residual voltage which appears across the arrester terminals when a discharge current is flowing through it [Hileman et. al (1991), Burke et. al (1981)].

(iv)Lower protective level (highest discharge voltage that appears between arrester terminals during specific conditions of a discharge operation [Hileman et. al (1991), Burke et. al (1981)].

(v) Faster switching capability compared with a spark gap time response.

1.9. Application of ZnO Varistor

1.9.1. Zinc-Oxide (ZnO) Varistor as surge arresters for protection of series compensation stations:

The transmission of electric energy over long distances by high voltage AC overhead transmission lines is limited by the inductance of the line. Above a certain length, the magnitude of which depends on the geometry of the system and its voltage, the voltage drop across the inductive impedance reaches a value which makes the system ineffective. There are two countermeasures to reduce or completely avoid the inductive current and thus to increase the efficiency of an overhead line: The installation of series compensation (SC) stations within the AC overhead line [CIGRÉ Publication 33/14-05] or the transmission by high voltage direct current (HVDC). As other stations, SC stations are protected by standard surge arresters against lightning overvoltages. A circuit diagram of an SC station is shown in Figure 1.7.

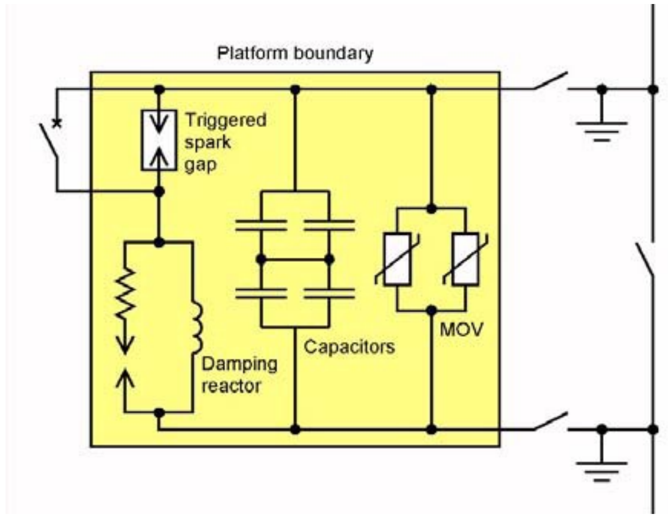

Figure 1.7: Circuit diagram of SC station with MOV [CIGRÉ Publication 33/14-05]

The purpose of series compensation is to reduce the line voltage drop, to limit the load dependent voltage drops, to reduce the transmission angle combined with an increase of system stability and increase the transmission capability. To design surge arrester banks system data are needed as the rated voltage, the rated impedance, the rated current, the short circuit power, the overload current cycle and the protection strategy during external and internal fault. For specified fault clearing sequences the metal oxide varistor (MOV) has to withstand stresses from external faults. This includes generally two subsequent faults, as they occur for example at a non-successful auto-reclosure. At internal faults the bypass devices are allowed to operate. However the arrester must be designed to withstand stresses from two subsequent internal faults. Using all given data an appropriate control and protection strategy can be established and coordinated resulting finally in energy rating including redundancy and protective level of the surge arrester bank. The arrangement of surge arresters in parallel within a bank leads to an uneven current distribution between them in case of overvoltage. This effect is caused by the high degree of non-linearity of that part of the voltage-current characteristic where the surge arrester has to operate in case of a system fault. To keep this uneven current distribution within a certain limit, e.g. ±5%, all columns belonging to one surge arrester bank have to be measured in a current distribution test. Another main aspect is the short circuit behavior of a single surge arrester as a part of a complete surge arrester bank. To avoid damage of further units in case of arrester failure only surge arresters with pressure relief device should be used. These surge arresters can be installed on the platform in that way that the diverter nozzles show in a direction where the released gases do not damage the surrounding units. Surge arresters with porcelain housing can be destroyed in a secondary break as a result of pressure relief. Therefore surge arresters with composite housing are more suitable as they keep all their mechanical properties after a pressure relief.

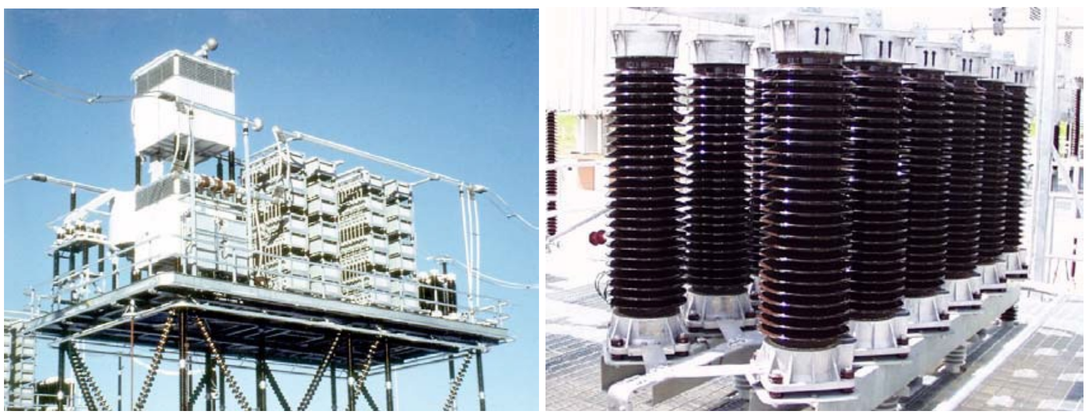

Figure 1.8: SC station (left) and surge arrester bank (right) [CIGRÉ Publication 33/14-05]

1.9.2. Surge Arresters for Protection of High Voltage Direct Current Stations (HVDC)

An HVDC station rather a complex system includes a number of different surge arresters for protection of the different pieces of equipment. As indicated in [CIGRÉ Publication 33/14-05] and Figure 3, there are basically six types of surge arresters, which are commonly denominated by “A” to “F”.

Type A: AC bus arresters which are located close to termination of incoming AC lines and close to transformers to give protection against lightning surges.

Type B: Valve arresters to protect the thyristor valves from excessive overvoltages. The protective level shall be as low as possible since the costs of the valves are roughly directly proportional to the insulation level across the valves.

Type C: Converter unit arrester for protection against overvoltages at the converter DC bus

Type D: DC bus or DC line arrester to protect the DC switchyard equipment connected to the DC pole.

Type E: Neutral bus arrester to protect the neutral bus and the equipment connected to it. Neutral bus arresters may be subjected to very large energy discharges in case of ground faults.

Type F: AC and DC filter arrester to protect the AC and DC filter reactors and capacitors

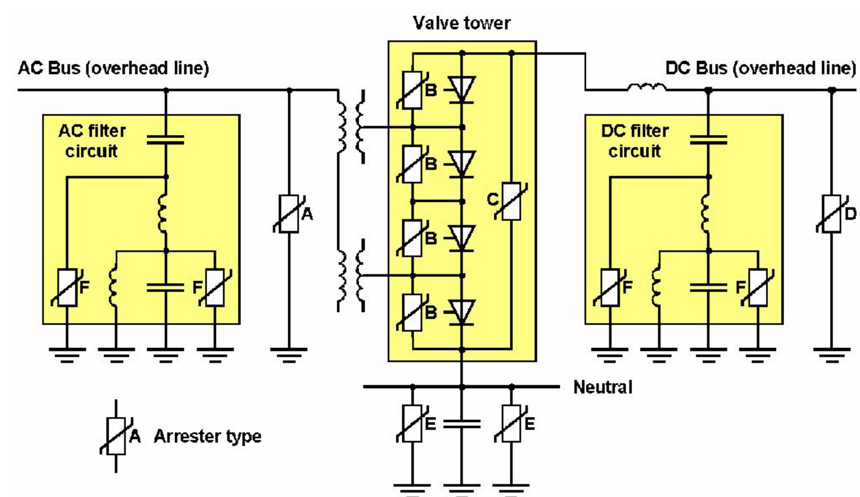

Figure 1.9: Circuit diagram of HVDC station with arresters [CIGRÉ Publication 33/14-05]

Figure 1.10: Examples of B (left) and A arresters (right) in a HVDC station [CIGRÉ Publication 33/14-05]

The dimensioning of the “B” and “C” arresters for protection of the semiconductors of the valve tower is particularly critical. On the one hand, the protection level must be maintained as low as possible in order to protect the very sensitive semiconductors and to minimise the number of these very costly components. On the other hand, the voltage and current wave shape across the arresters is extremely non sinusoidal and dependent on the load conditions and power flow of the HVDC station. As a consequence, the power dissipation of the arrester is variable with the load conditions and it is difficult to find the right compromise between protection of the valve tower and safe operation of the arrester. Simulation of the HVDC station including the various possible faults is an important tool for determination of the arrester voltage and current stress [CIGRÉ Publication 33/14-05]. Tests on prorated sections of arresters for HVDC application have shown that the power dissipation under these loads is different as compared to pure sinusoidal waves shapes [Horiuchi (1988), Kai Steinfeld (2003)].

1.9.3. Effect of Static Fault Current Limiter uses along with Zinc-Oxide (ZnO) Varistor on Distribution Power Quality

High demand for sustainable electric energy makes the use of ***Distributed Generators*** (DGs) inevitable for future systems [Najafi (2012)]. However, introducing DGs into distribution networks increases fault current levels with potential for causing serious damage to power system apparatus. If these currents are allowed to persevere, they will cause insulation failure, feeder melting, explosion and personnel risk. Machine windings and bus-bars may also suffer mechanical damage due to the excessive magnetic forces during fault periods. Increasingly power quality during fault and recovery periods is also adversely affected. To alleviate these problems, a Static Fault Current Limiter (SFCL) is a potential solution. The use of SFCL is an attractive alternative to limit the fault current levels in such a case. The SFCL however exhibits harmonic generation due to the switching of the Insulated Gate Bipolar Transistor (IGBT).

High switching frequency of the IGBT causes significantly high rate of change of voltage and current waveforms that may result in failure of the semiconductor switches. For suppressing the instantaneous voltage rate-of-change (dv/dt) at the turn off instant, ***a Zinc-Oxide (ZnO) Varistor is connected in parallel with the static bridge/limiting inductor combination***. The Varistor provides a high resistance as the voltage across it is less than the reference voltage. Otherwise, it offers a very small resistance to current flow. The parameters of a typical ZnO are tabulated in Table 1.3, where the reference voltage is selected at 80% higher than the rated phase voltage [Najafi (2012)].

Table 1.3: The parameters of a typical ZnO [Najafi (2012)]

CHARACTERISTICS OF ZINC-OXIDE VARISTOR		
$i_{ZnO} = p\left(\frac{v}{V_{ref}}\right)^q$	Symbol	Quantity
	P	1 kA
	q	11
	V_{ref}	15.6 kV (RMS)

1.9.4. Wide Areas of Application for Varistors

A wide selection of types is available to cover very different requirements for protective level and load capability.
The table below summarizes them:

[1]Telecommunications
Private branch exchanges
Telephone subscriber sets
Telephone pushbutton modules
Teleprinters
Answering sets
Power supply units
Transmitting systems
Fax machines
Modem
Cellular (mobile) phones
Cordless phones
Chargers
Car kits
Radios

[2]Industrial controls
Telemetering systems
Remote control systems
Machine controls
Elevator controls
Alarm systems
Proximity switches
Lighting controls
Power supply units
Ground fault interrupters
Gas heating electronics
Electronic ballasts
LCDs
Beacon lights

[3]Power electronics
Bridge rectifiers
Brake rectifiers
Electric welding
Electric vehicles
Switch-mode power supplies
High-power current converters
DC/AC converters
Power semiconductors

[4] Power engineering
Transformers
Inductors
Motor and generator windings
Transmission line lightning arresters

[5] Automotive electronics
Central protection of automotive electrical systems
Load-dump protection
Anti-skid brake systems
Trip recorders
EMP/NEMP protection
Engine control units
Generator rectifiers
Central locking systems
Trip computers
Wiper motors
Power window systems
Airbag electronics
Car phones
Seat memories

[6] Traffic lighting
Traffic signals
Runway lighting

[7] Medical engineering
Diagnostic equipment
Therapeutic equipment
Power supply units

[8] Data systems
Data lines
Power supply units
Personal computers
Interfaces
ASIC resets
Micro controllers
I/O ports
Keyboards
Handheld PCs

[9] Stepped protection
Microelectronics
EMI/RFI suppression

[10] Entertainment electronics
Video sets
Television sets
Slide projectors
Power supply units
HIFI equipment
Set top boxes

[11] Household electronics
Washer controls
Dimmers
Lamps
Quartz clocks
Electric motor tools
Thermostats

[12] Replacement of
Suppressor diodes
Diodes
Capacitors

If semiconductor devices like diodes, thyristors and triacs are parallel with ZnO varistor for protection, they may do with lower reverse-voltage strength. This leads to a marked cost reduction and can be the factor that really makes a circuit competitive.