

# HIGH GRADIENT METAL OXIDE SURGE ARRESTER BLOCK FOR VFTO APPLICATIONS

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**Abstract:** Metal oxide surge arrester plays important role in protection of power system against various surges. The present design of arrester is inoperative against very fast transient overvoltages (VFTOs). The height of arrester increases with voltage rating and so potential distribution is highly non-uniform because of its capacitive effect. A new composition of arrester material is proposed and arrester samples are prepared using conventional and microwave sintering processes at different temperature and holding time. All prepared samples are analyzed and one among them is chosen for VFTO application. The chosen sample gives arrester with reduced grain size, height, capacitance and leakage current. The density and non-linear coefficient are improved. Because of these good parameters, the arrester with new composition sintered using microwave furnace, might be used for successful protection of power system against VFTO.

**Key words:** Breakdown voltage, leakage current, metal oxide surge arrester, microwave sintering, non-linearity, very-fast transient overvoltage (VFTO).

## 1. Introduction

Zinc Oxide arresters are polycrystalline semiconducting ceramic devices consist of various additives and dopants embedded in it [1-3]. It is a voltage dependent switching device, which behaves as high resistors for low electric field and offers low resistance for high electric field [3]. It is widely used as surge suppressor in high voltage power network and voltage regulation in low voltage devices because of its outstanding non-linear characteristics and energy absorption capability [4].

The operating voltage of power system network increases rapidly. The insulation level and cost of power system apparatus depend upon the maximum possible overvoltage stress on power system and protection behavior of surge arrester. So there is a challenge for the manufacturer to improve surge arrester performance like higher non-linear characteristics and fast transition from non-conducting mode to conducting mode against all possible overvoltages. When the voltage level of power system is increased, then it is obvious that the height of arrester is also increased. Valsalal et al [5] discussed

that the height of arrester column is increased with voltage rating and hence the voltage distribution is more non-uniform because of capacitance effect. This capacitance effect is significant for very fast transient overvoltage (VFTO) having front time of the order of nanoseconds. This VFTO is generated with the introduction of gas insulated substation (GIS) in power system. The existing commercial arrester will not protect the system against VFTO because of delay in initial response of the arrester. The cause for the delay is presence of stray capacitance, which plays major role during very fast transients [5-7]. Now there is a question of reducing stray capacitance by reducing arrester's height which enhances the uniformity of voltage distribution on the arrester column. This is achieved by designing the surge arrester with high voltage gradient material so that the height of surge arrester can be reduced [8, 9].

The active surge arrester block comprises of ZnO as a majority with small amount of basic additives, such as Bi<sub>2</sub>O<sub>3</sub>, Sb<sub>2</sub>O<sub>3</sub>, Co<sub>2</sub>O<sub>3</sub>, MnO<sub>2</sub> and few other additives [10]. These additives play a crucial role to achieve the better microstructural and electrical parameters. Particularly, the addition of Sb<sub>2</sub>O<sub>3</sub> with ZnO results a spinel phase formation and its doping characteristics leads to the formation of inversion boundaries to manage grain growth and microstructure development of arrester [11]. The addition of Bi<sub>2</sub>O<sub>3</sub> takes much responsibility to achieve high non-linearity combined with Sb<sub>2</sub>O<sub>3</sub> which has a standard quality for controlling the grain growth during sintering. Simultaneously, the other oxides namely Cobalt (Co) and Manganese (Mn) are incorporated into the grains of ZnO to increase their conductivity [12]. It is well known fact that the sintering of these compositional pressed pellets results a formation of three basic phases such as spinel (Zn<sub>7</sub>Sb<sub>2</sub>O<sub>12</sub>), pyrochlore (Zn<sub>2</sub>Sb<sub>3</sub>Bi<sub>3</sub>O<sub>14</sub>) and bismuth rich (a- or b-Bi<sub>2</sub>O<sub>3</sub>) phases from lower to higher temperature [11]. These phase formation determine the non-linear characteristic of varistor by forming Schottky barriers at the ZnO grain boundaries. The breakdown field and nonlinearity depend on the number of effective boundaries per unit volume and

conductivity of ZnO grains [3]. Alternation in small ratio of dopants and sintering effects can significantly affect the phase formation of boundary, nonlinearity, breakdown field and conductivity of single grain. These microstructural variations enhance the electrical behavior of arrester block.

## 2. Problem statement

Five samples of arrester block are considered for the analysis. The first sample (CA) is existing commercial arrester block collected from the manufacturer. The second (CS1) and third (CS2) samples are prepared by adding two new additives with basic composition using conventional process at different sintering effect. The fourth (MW1) and fifth (MW2) samples are made for the same composition using microwave sintering with different sintering effect.

The conventional sintering process takes long time to complete the heating process and it is difficult to control the grain growth and the density of the sintered disc [13]. Moreover, there is temperature gradient from the surface of the pellet to the inside of the pellet [14, 15]. This leads to non-uniform heating effect throughout the sintering disc and results a non-uniform voltage and current distribution from surface to core of a disc. Because of these non-uniformities, the voltage gradient and current handling capability of arrester affected greatly.

The non-uniformity in voltage and current distribution is reduced using microwave sintering and it generates the heat within the material first and then heats the entire volume [14]. This sintering process shortens the sintering time and enhances the microstructural and electrical properties of sintered disc at lower level temperature [13]. This sintering process can also densify the arrester disc at rapid rate and at lower temperature compared with conventional sintering method [12],[16]. So the microwave sintering is chosen to achieve uniform heating of sintering disc which leads to higher voltage gradient and current density. This will give reduced height and diameter of arrester column.

## 3. Analysis of existing commercial arrester.

A commercially available arrester block, with rated voltage of 9kV and discharge current of 5kA is used for the analysis. The composition, sintering method, temperature and holding duration are unknown for the existing commercial arrester. The test results of arrester block are given in Table 1. The surface microstructural image of the arrester is shown in Fig 1. The white region between the zinc oxide grains are bismuth-rich intergranular layer and it forms a continuous network path between the ZnO grains. The average size of grain is about 12.54 $\mu$ m.

Table 1  
Test results of commercial arrester block/mm

Grain size	12.54 $\mu$ m
Voltage gradient	202V
Leakage current	8.9 $\mu$ A
Non-linear coefficient	37
Density	93.65%

The reason for higher grain size might be the effect of high temperature and holding time during sintering process. The voltage gradient is found as 202V/mm and it shows that the composition might have failed to inhibit the growth of grain during sintering. The leakage current of arrester block is measured as 8.9 $\mu$ A and this high value of current shows the reduced life span of arrester.

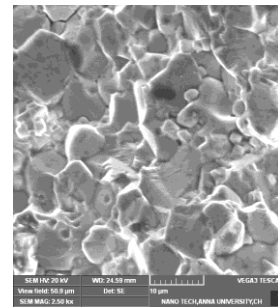


Fig. 1. SEM image of surface of commercial arrester block

After making complete study on commercial arrester, it is observed that the performance is not satisfactory for successful protection of power system equipment against all types of overvoltages from microseconds to nanoseconds. So an attempt is made to prepare arrester for better performance with new ingredients using microwave sintering. Lei Ke et al [1] revealed that the rare-earth doping can greatly improve the voltage gradient and non-linearity with reduced leakage current.

The voltage gradient is increased by adding rare earth element having increased atomic number [17]. Hence, the Gadolinium trioxide ( $Gd_2O_3$ ) is added as rare earth element along with basic additives because of its larger ionic radius. In addition to this, Vanadium pentoxide ( $V_2O_5$ ) is added to get higher densification with smaller grain size. This composition is sintered with microwave furnace at relatively low temperature for obtaining arrester block with new composition having greater density, increased non-linear coefficient and reduced leakage current [18-21]. Finally all samples are compared for better performance.

## 4. Experiment

Reagent grade raw materials are used for the fabrication of ZnO arrester samples with composition of 88.1wt% of ZnO and small ratio of  $Bi_2O_3$ ,  $Sb_2O_3$ ,  $Co_2O_3$ ,  $V_2O_5$ ,  $Cr_2O_3$ ,  $MnO_2$  and  $Gd_2O_3$ . The weighed

powders are milled by using high energy ball with acetone as a wetting agent and zirconia ball as a milling media in a nylon bottle for 6 hours. The ratio of powder to balls is chosen as 1:20. After milling, the powders are heated at 120°C for 24 hours and calcined at 600°C for 2 hours. Agate/mortar is used to pulverize the calcined powder after adding the 2wt% of PVA (Poly Vinyl Alcohol) and granulated by sieving 100 mesh screen. The prepared powder is filled in a die and placed in uniaxial pressing machine. The pressure of 200Mpa is applied to compact the powders to form the disc. The pressed pellets are sintered with both conventional high temperature furnace and microwave furnace. The conventional sintering process is carried out at a temperature of 1000°C with duration of 1 hour (CS1) and 2 hours (CS2). Similarly, pressed pellets are sintered in microwave furnace at a same temperature of 1000°C with duration of 20 minutes (MW1) and 30 minutes (MW2). The lapping and grinding machines are used to form the final dimension of the sintered pellets. The silver paste is applied on both the faces of the sintered disc and heated at 600°C for 20 minutes which is acting as a conducting electrode. Now the arrester block is ready for electrical testing.

## 5. Results and Discussions

To analyze the microstructural properties of the arrester, it is essential for both faces to be lapped, grinded with SiC paper, polished with Al<sub>2</sub>O<sub>3</sub>, and chemically etched with 1wt% of hydrochloric acid ethanol solution for few seconds. The prepared sample is examined by Scanning electron Microscope (SEM, Tescan-vega3) and its microstructure is shown in Fig 2.

### 5.1 Grain size

The microstructural observation shows the secondary phases comprising of Vanadium, Bismuth and Antimony content forming boundary at the surface of ZnO grains. The grain size of ZnO decreases significantly because of addition of Gadolinium with different sintering effect. The variation in boundary formation and grain sizes are observed from the images because of different sintering process, temperature and holding time.

The average size of a grain (d) is determined by lineal intercept method using the Equation 1 [21].

$$d = \frac{1.56L}{MN} \quad (1)$$

Where L is a random line length, M is a magnification of the micrograph and N is a number of grains intercepted by the random line.

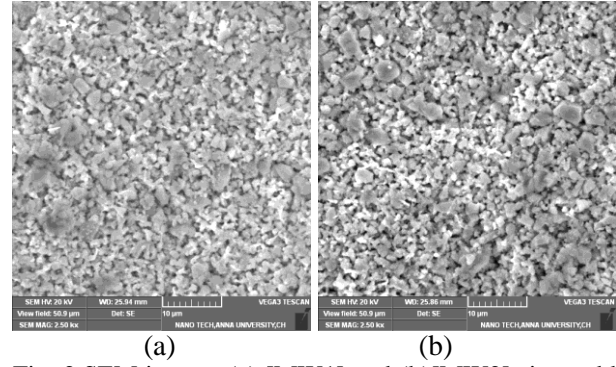


Fig. 2.SEM images (a) [MW1] and (b)[MW2] sintered by microwave furnace at 1000°C for 10 and 20 minutes respectively.

The variation in average size of grain is observed from different samples and it is shown in Figure 3. The commercial arrester block gives large grain size of about 12.54μm. The reason might be higher sintering temperature, higher holding time and the additives failed to control the growth of grain. The average size of grain increases significantly with higher holding time for both cases of sintering process (conventional and microwave). The conventional sintering process shows larger grain size because of its higher holding time to achieve the densification. But the sample sintered by microwave furnace for 10 minutes (MW1) shows still smaller grain size of about 2.2μm.

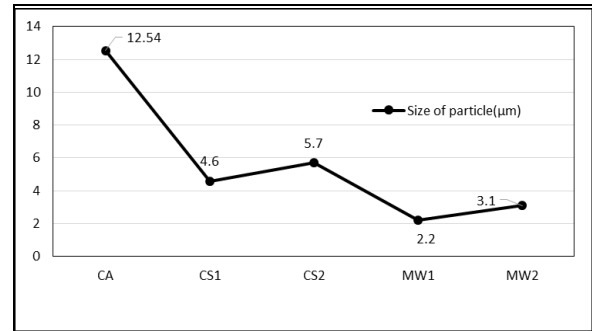


Fig. 3.Grain size of commercial arrester block, and samples sintered by conventional and microwave processes.

### 5.2 Density

The relative Densities of the sintered bodies are determined using Equation 2 [22].

$$\text{Relative Density (\%)} = \frac{\rho_a}{\rho_t} * 100 \quad (2)$$

Where,  $\rho_a$  is the apparent density of the pellet (g/cm<sup>3</sup>) obtained by Archimedes method and  $\rho_t$  is a theoretical density of ZnO (5.61 g/cm<sup>3</sup>). The variations in relative density of sintered samples are shown in Fig 4. The commercial arrester (CA) block attains the densification similar to conventional sintered samples. The sintering temperature of commercial arrester block is unknown but it might have sintered at high temperature (>1000°C) because of its larger grain size.

The conventional processed samples are sintered at relatively low temperature. The conventionally sintered samples (CS1 and CS2) failed to achieve higher densification even holding duration is much higher than microwave sintered samples. The sample prepared using microwave sintering at 1000°C (MW2) reaches higher densification of about 97% of its theoretical density.

The microstructural properties show that the samples sintered by microwave furnace gives better results compared with conventional sintering process along with the additives of Vanadium and Gadolinium.

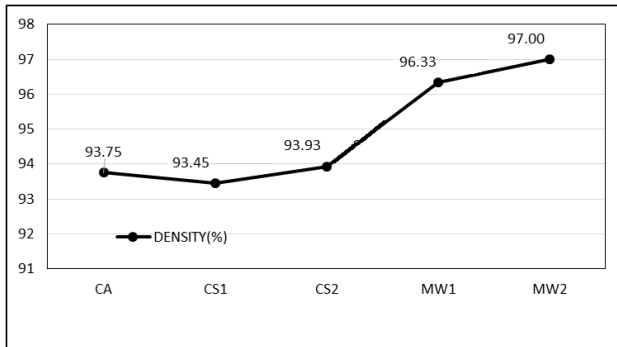


Fig. 4. Density

### 5.3 V-I Characteristics and voltage gradient

The electrical parameters of arrester are measured by using high voltage DC electrometer setup as per the test circuit shown in Fig 5. The breakdown voltage is determined at a current density of 1mA/cm<sup>2</sup>. The voltage gradient (E1mA/cm<sup>2</sup>) is found by  $(E1\text{mA}/\text{cm}^2)/t$ , where 't' is the thickness of the sample.

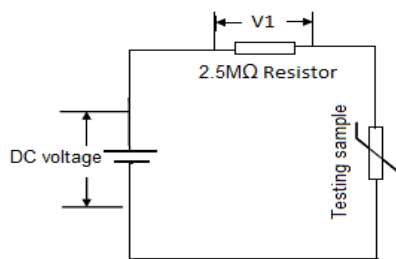


Fig. 5. V-I test circuit

The V-I characteristic of commercial arrester block and samples sintered by conventional method and microwave are shown in Fig 6.

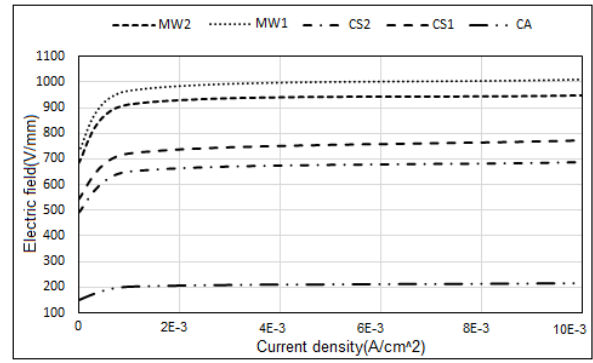


Fig. 6. V-I characteristic of different samples

From the V-I characteristics, it is observed that the breakdown voltage of commercial arrester is only 202V. The lower breakdown field of commercial arrester block is because of their larger grain sizes. The MW1 sample gives higher breakdown voltage of about 0.965 kV. In similar way, the voltage gradients of all samples are presented in Fig 7. The voltage gradient of commercial arrester blocks is only 202V/mm. Because of higher sintering duration, CS1 and CS2 samples results larger grain size, this leads to voltage gradient of 720V/mm and 652V/mm respectively. The voltage gradient of MW1 and MW2 samples are still higher about 965V/mm and 912V/mm respectively.

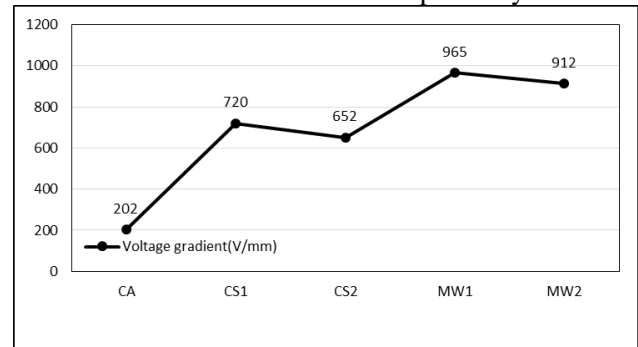


Fig. 7. Voltage gradient

In Section 1, it is mentioned that the arrester with higher voltage gradient reduces its height. This is because of addition of Gadolinium and it inhibits the growth of grain even for long holding time. By comparing their heights, the height requirement of the arrester samples sintered with microwave furnace is about 4-5 times less than commercial arrester (CA). The variation in total height of surge arrester for given voltage level in per unit length is shown in Fig 8.

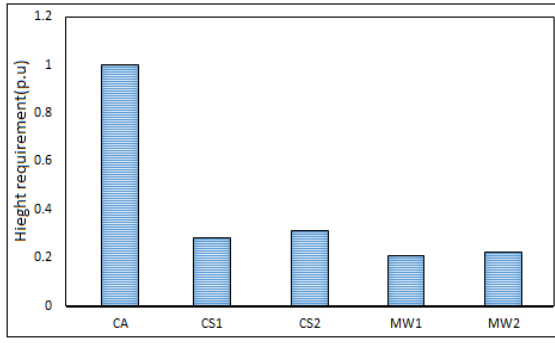


Fig. 8.Total height requirement of arrester in p. u

If the height of the arrester is reduced, the stray capacitance of the surge arrester is also reduced [23]. So uniformity of voltage distribution is enhanced along the arrester column during both non-conduction and conduction modes of arrester. For given system voltage, the commercial arrester block require higher height and so non-uniformity in potential distribution is more. But the samples sintered by microwave method gives reduction in height requirement of arrester and so uniformity in potential distribution enhanced with reduced capacitive effect.

The non-linear coefficients ( $\alpha$ ) of various samples are computed using Equation 3 [24] and graphically shown in Fig 9. The voltage at 1mA and 10mA are directly observed from the V-I characteristic of the arrester (Fig 6).

$$\alpha = 1/\log\left(\frac{V_{10\text{mA}/\text{cm}^2}}{V_{1\text{mA}/\text{cm}^2}}\right) \quad (3)$$

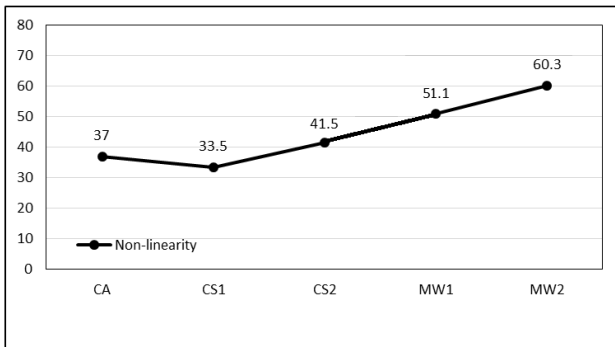


Fig. 9.Non-linear coefficient ( $\alpha$ )

The residual voltage of the arrester greatly depends on its non-linear coefficient ( $\alpha$ ). From Fig 9, it is clearly observed that the commercial arrester has  $\alpha$  value of 37. But, the values of  $\alpha$  for sample CS1 and CS2 are 33.5 and 41.5 respectively. The microwave sintered samples MW1 and MW2 give better values of  $\alpha$ , 51.1 and 60.3 respectively.

The requirement of insulation strength of power components is reduced if arrester prepared using microwave sintering (MW2) is used for protection. The other advantage of increasing  $\alpha$  is improving the initial

response of the arrester, with front time of 5 ns [5]. Hence, it is possible to minimize the delay for transition from non-conduction to conduction mode especially for VFTO. Economically and technically, with higher value of  $\alpha$ , residual voltage of arrester and the insulation levels of the power system are reduced. Moreover the stresses caused because of overvoltages are reduced on power components.

#### 5.4 Leakage current

The life span of the arrester depends on the leakage current and is calculated by applying  $0.75 \text{ E1mA}/\text{cm}^2$ . This higher leakage current deteriorates the life of the surge arrester [25]. The product of kilovolt and microampere leakage current also results considerable power loss during the entire operating span of surge arrester. The leakage current of the different samples are shown in Fig10. The leakage current of commercial arrester is  $8.9\mu\text{A}$ , which is not desirable. The leakage current of samples CS1 and CS2 are relatively higher than samples prepared by microwave sintering. Because of higher densification, the sample MW2 takes leakage current of only  $2.1\mu\text{A}$ .

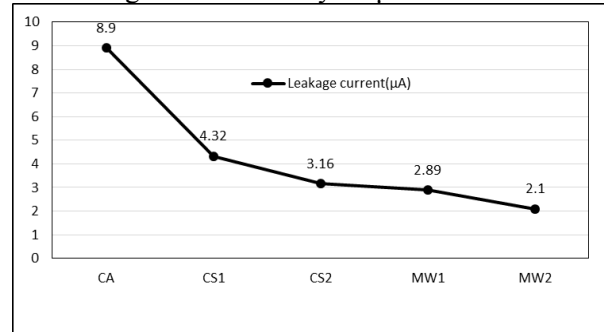


Fig. 10.Leakage current

#### 5.5 Capacitance of arrester blocks

The IEEE working group 3.4.11 indicated that arrester blocks have dynamic behavior for front time (time-to-crest) of  $0.5\text{--}45\mu\text{s}$  [26]. The front time of incoming surge especially below  $1\mu\text{s}$  causes a time lag between the peak of residual voltage and discharge current. This is because of the presence of the capacitive effect of the arrester [5-7], [27]. Hence the arrester block having less capacitive effect with higher voltage gradient material will reduce the time lag between the residual voltage and discharge current. Fig 11 represents the capacitance of the prepared samples by applying  $1\text{V}_{\text{rms}}$  with frequency range from 100Hz to 1MHz plotted by impedance analyzer (Wayne Kerr, 6500B). The sample CS1 gives the lowest value of capacitance,  $0.0906\text{nF}$  at 100Hz and  $0.053\text{nF}$  at 1MHz. The capacitance of sample prepared by microwave



sintering (MW2) gives the capacitance value of 0.189nF at 100Hz and 0.065nF at 1MHz. The reduced value of capacitance definitely improves the initial response of arrester [27].

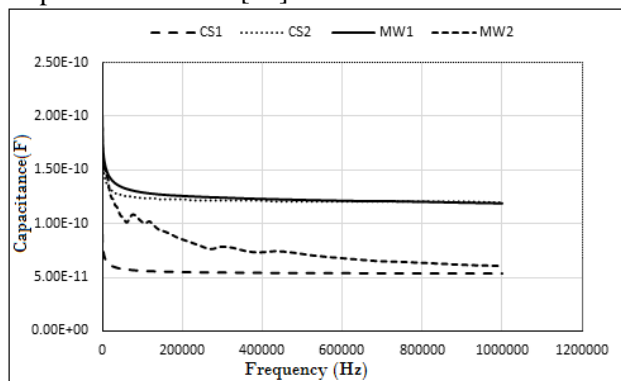


Fig. 11. Capacitance of arrester blocks

## 6. Conclusion

The micro structural and electrical properties of metal oxide arrester have been improved using microwave sintering method with additives of Vanadium and Gadolinium at relatively low temperatures. The sample prepared by microwave sintering (MW2) gives superior results compared with conventional sintering process. The value of breakdown strength is 912V/mm and nonlinearity constant of 60.3. The leakage current is only 2.1 $\mu$ A. The height and capacitance value of the newly prepared arrester block are less. With these good parameters, it is possible to achieve improvement in the initial response of arrester so that the arrester prepared using microwave sintering with new elements might be used for protection of power system against VFTOs.

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## Biographies

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