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Development of metal oxide arrester block using a rare earth element for very fast transient overvoltage applications

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Abstract: The protection ability of metal oxide arresters against switching, lightning, and steep current surges has been well proven. On the contrary, during the invasion of very fast transients, the existing arrester fails to operate due to delay in its initial response. In order to decrease the delay, it is imperative to improve the electrical properties of the arrester such as nonlinearity and voltage gradient with reduced capacitive effect. In this context, new arrester blocks are developed with the addition of a rare earth element, namely scandium trioxide (Sc_2O_3), and then sintered with a microwave sintering process. Owing to the uniform heat distribution characteristic and the requirement of a low sintering temperature, the microwave sintering process provides better microstructural and electrical properties than the conventional sintering process. From the observed results of prepared arrester blocks, one among them is chosen, which contributes a higher voltage gradient (790 V/mm), better nonlinear coefficient (55), and the least leakage current (2.9 μA). Moreover, the chosen arrester block gives a lower block capacitance of 0.0985 nF at 100 Hz. Hence, this arrester block can afford better protection of the power system against very fast transients.

Key words: Gas insulated substation, metal oxide arrester, microwave sintering, rare earth element, very fast transient overvoltages

1. Introduction

The protection of a power system greatly hinges on the V-I characteristic of the metal oxide arrester. It comprises several arrester blocks, which are stacked in series and parallel. In these blocks, voltage and current rating depend on the height and diameter of the arrester blocks respectively. These arrester blocks consist of a complicated ZnO grain network between boundaries, which are connected in parallel and series [1].

The performance of a complete surge arrester solely depends on the behavior of a single ZnO grain and its boundary formation. Therefore, the formation of the boundary and enhancement of grain conductivity are accomplished through optimal doping of small ratios of Bi_2O_3, Sb_2O_3, Co_2O_3, Cr_2O_3, MnO_2, etc. [2]. The inclusion of small dopants and optimal sintering effect can improve the performance of the arrester when it faces surges. Moreover, it is well known that the arresters provide superior protection to the power system against invasions of surges like switching, lightning, and steep current. This is because of the successful potential breakdown of the arrester within a required time with respect to front time of respective current surges. Under this circumstance, the residual voltage reaches the peak before the peak of current surge peak, which ensures a successful 'turn on' of the surge arrester [3].

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With the introduction of a gas insulated substation (GIS) in a power system, the generation of very fast transient overvoltages (VFTOs) increases and this causes a higher number of insulation failures in the power system [4]. Because of its very high steepness (nanosecond surges), a commercially available arrester fails to 'turn on' within the required time. Consequently, potential breakdown of the arrester happens with delay. This causes a time lag between the peak of residual voltage and current surge (residual voltage attains a peak after the current peak) [5–8] and leads to failure in arrester operation during a VFTO. This time lag (slow response) can be minimized by reducing the arrester capacitance. With this background, an attempt is made to reduce the arrester capacitance with modified arrester material and advanced material processing.

It is also known that a high voltage gradient arrester block shortens the height of the arrester assembly [9–11] for high voltage applications. This can be achieved with optimal doping of a rare earth element with arrester composition. Furthermore, better sintering effect improves the densification and relative permittivity with less grain growth level. These are feasible with the microwave sintering process owing to its uniform heat distribution of the entire arrester block even at low sintering temperatures [12]. Hence, modification of dopants (rare earth elements) and the sintering effect can considerably enhance the nonlinearity and voltage gradient and reduce leakage current and arrester capacitance. With this background, this paper discusses the preparation of a new arrester block to improve the microstructural and electrical properties.

2. Problem statement

The capacitances of the arrester (block and stray capacitances) decide the fastness of arrester operation during very fast transients. An arrester with a higher value of capacitances has more delay in its operation because potential breakdown happens only after the diminishing of capacitances. These capacitances hinge on the height of the arrester column and its material properties [6]. Therefore, reduction of arrester capacitance is accomplished with high gradient arrester material [7,8] and thereby arrester height is reduced noticeably. Moreover, the modified arrester composition and alternative sintering process decrease the block capacitance. Therefore, a rare earth element, namely scandium trioxide (Sc_2O_3), is suggested for improving the arrester performance. It has excellent ability to restrict the grain growth during the heating process owing to its strong pinning effect [11]. Consequently, considerable reduction in grain size is achieved.

In order to reduce the block capacitance, a modified sintering process, namely microwave sintering, is used. The conventional sintering process provides a temperature gradient from the exterior to the interior volume of the arrester block, causing a nonuniform sintering effect [13]. On the other hand, the microwave sintering process heats the entire volume of the disk uniformly [12] and so densification can be enhanced even at low temperatures [14–16]. As a result, it gives increased nonlinearity and reduced grain size and leakage current. Hence, new arrester blocks are developed with doping of scandium trioxide (Sc_2O_3) along with the basic composition and microwave sintering effect. With these consequences, the overall performance of the surge arrester is improved for VFTO applications.

3. Experiment

Reagent raw materials were used for the preparation of the arrester block, which comprised a major percentage of ZnO and a small percentage of Bi_2O_3, Sb_2O_3, Co_2O_3, Cr_2O_3, MnO_2, and Sc_2O_3. The weighed powders were milled by a high energy ball mill with a wetting agent. The powders were allowed to mill for 10 h with zirconia balls and the ratio between powders and balls was 1:10. Subsequently, calcination of milled powder was carried out at 600 °C for 2 h. PVA at 2 wt.% was added to the calcined powder and pulverized by agate/mortar.

In order to obtain uniform grain sizes, the powders were sieved through a 100-mesh screen. The formation of arrester disks was achieved by uniaxial pressing machine, applying a pressure of 150 Mpa.

Four arrester disks were molded with the same dimensions and these blocks were heated at different sintering effects. The conventional sintering process was carried out for two arrester blocks at a temperature of 1000 °C with two different holding times of 1 h and 2 h and then labeled as S1 and S2, respectively. Subsequently, another two blocks were heated by microwave furnace at a temperature of 1000 °C with 20 and 30 min of holding time and then named S3 and S4, respectively. The prepared blocks were ground with a lapping machine to obtain the final dimension of the arrester blocks.

4. Results and discussions

The prepared arrester blocks were examined to analyze the microstructural and electrical properties.

4.1. Microstructural properties

The microstructural appearance of the arrester blocks was observed by scanning electron microscope and is shown in Figure 1. From the images, it is observed that variation in grains sizes is found between different samples. The addition of antimony (Sb) and scandium (Sc) controlled the growth of grains in all samples during sintering. Due to variation in sintering effect, microstructural properties display variation between the samples.

The average grain sizes of samples were calculated using Eq. (1) as in [10].

$$d = \frac{1.56L}{MN} \tag{1}$$

Here, L, M, and N are random line length, the magnification of the image, and the number of grains intercepted by the line, respectively. The computed grain sizes of prepared arrester samples are shown in Figure 2.

It is found that samples S1 and S2 give grain sizes of about 4.2 μm and 4.9 μm, respectively. This might be because of the higher sintering rate. With microwave sintering, samples S3 and S4 show smaller grain sizes of about 2.6 μm and 3.4 μm, respectively. Therefore, the microwave sintered samples could provide better voltage gradients compared with samples S1 and S2.

In order to obtain a higher nonlinear coefficient, densification of the arrester block needs to be computed and hence it was calculated using Eq. (2) as in [2].

$$Density\,(\%) = \frac{\rho_c}{\rho_t} * 100 \tag{2}$$

Here, ρ_c and ρ_t are respectively the calculated and theoretical values of densities. Figure 3 shows a computed value of densities for different samples. From the observed results, it is perceived that the conventional sintered samples give a maximum density of 96.9% even when holding durations are longer. However, the microwave sintered samples have a maximum density of 98.4% even with shorter holding durations. Hence, microwave sintered samples show better microstructural properties compared with conventional sintering samples.

4.2. Voltage gradient, nonlinearity, and leakage current

Electrical properties such as voltage gradient, nonlinearity, and leakage current were calculated using a DC source. The relationship between voltage and current of an arrester block is important to study its behavior.

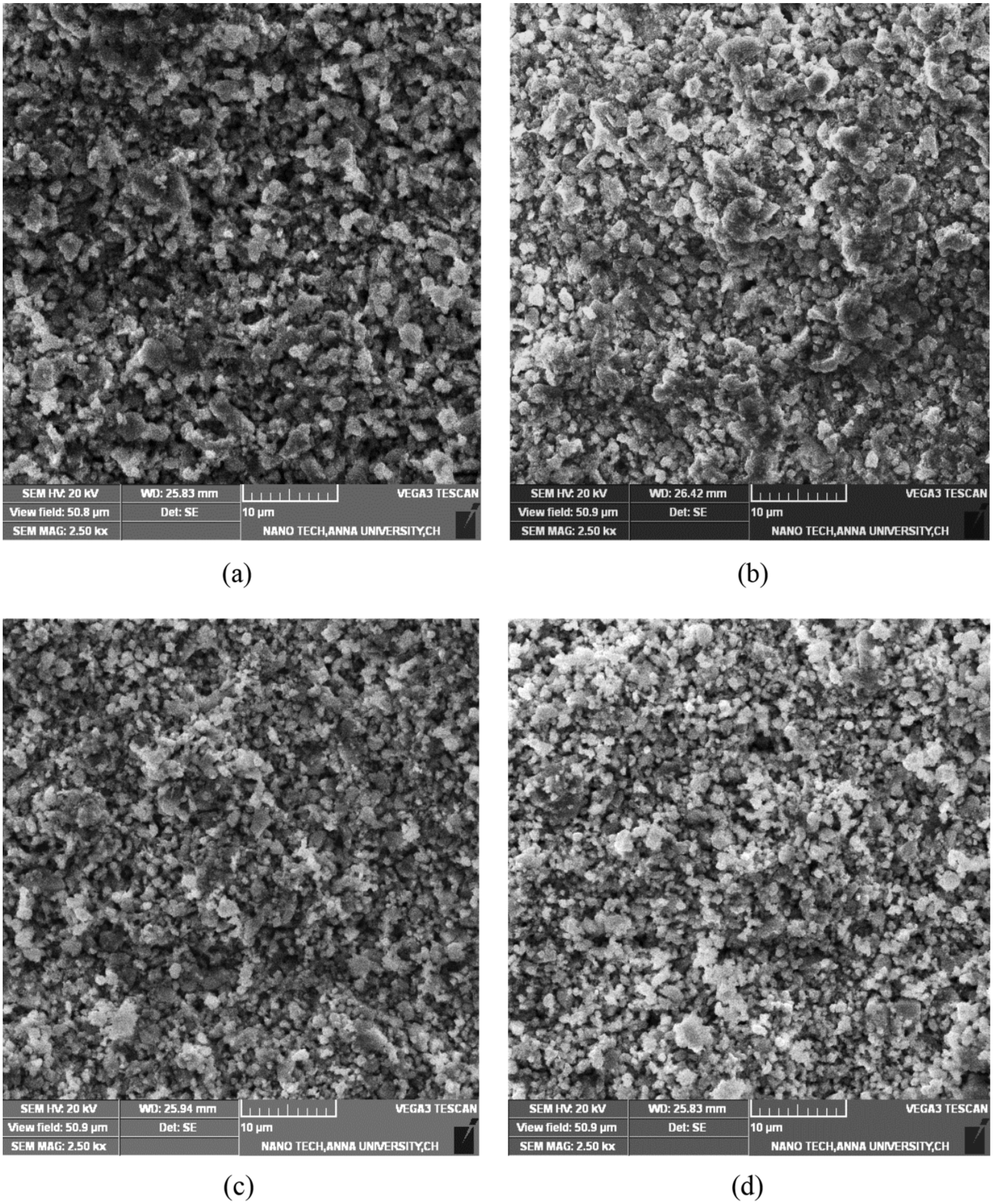

Figure 1. SEM image of samples: (a) S1, (b) S2, (c) S3, (d) S4.

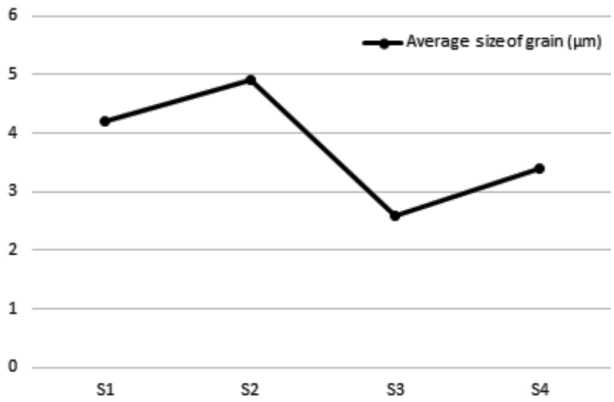

Figure 2. Average grain sizes of different samples.

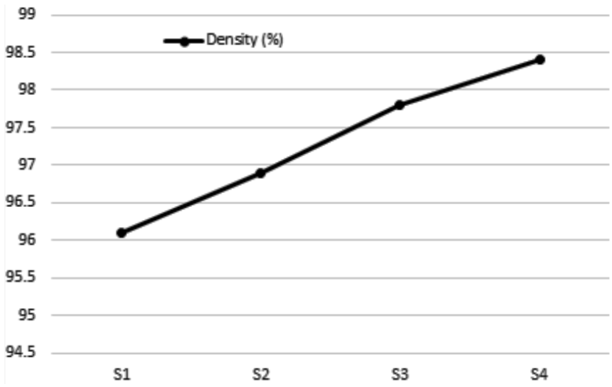

Figure 3. Densities of different samples.

Hence, V-I characteristics of all samples were observed using the circuit as shown in Figure 4 and the performances of all samples are given in Figure 5. Obviously, the average grain sizes of different samples determine their breakdown field strength. From the image, it is seen that the microwave sintered samples (S3 and S4) give better breakdown fields compared with S1 and S2.

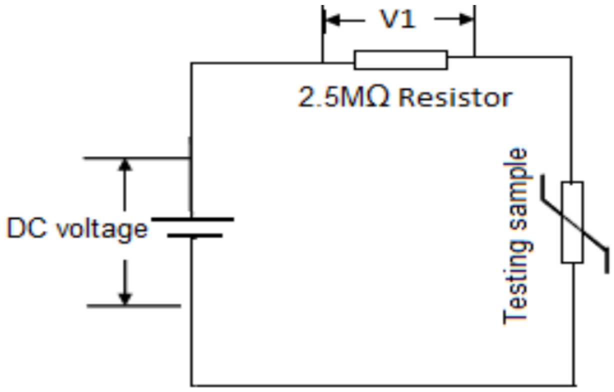

Figure 4. Test circuit for V-I characteristics.

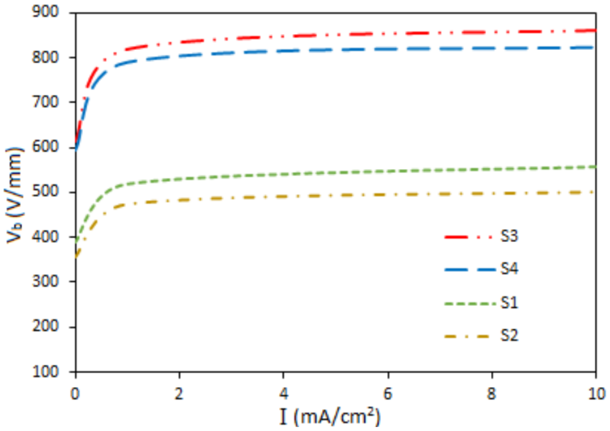

Figure 5. V-I characteristics of prepared arrester blocks.

From the V-I characteristics, the voltage gradient (clamping voltage of arrester while applying a current of 1 mA) of all prepared arrester samples was computed and is shown in Figure 6. Samples S1 and S2 give a smaller voltage gradient of 520 V/mm and 475 V/mm, respectively. This is due to their higher grain sizes. On the other hand, samples S3 and S4 have better voltage gradients of 820 V/mm and 790 V/mm, respectively.

The relation between the voltage and current of the arrester is given by Eq. (3) as in [2].

$$I = kV^{\alpha} \tag{3}$$

Here, α is a constant showing the nonlinear behavior of the surge arrester. It is well known that the ratio of additives and sintering effect could significantly vary the value of α. This nonlinear coefficient of the arrester block determines the clamping voltage across the arrester terminal during the incoming surge. It was calculated by observing voltage at 1 mA and voltage at 10 mA as given by Eq. (4).

$$\alpha = 1 \log\left(\frac{V10mA/cm^2}{V1mA/cm^2}\right) \tag{4}$$

Moreover, the clamping voltage is reduced with increased nonlinearity. As mentioned in Section 1, the more nonlinear material also increases the initial response of the arrester. Figure 7 represents the nonlinear coefficient of the arrester block samples. From that, microwave sintered samples S3 and S4 give higher nonlinearity of about 46 and 55, respectively. The higher the nonlinearity, the better the energy suppression by the arrester during the invading of surges. The conventional sintered samples (S1 and S2) contribute a maximum of 41, which shows the lower performance compared to S3 and S4.

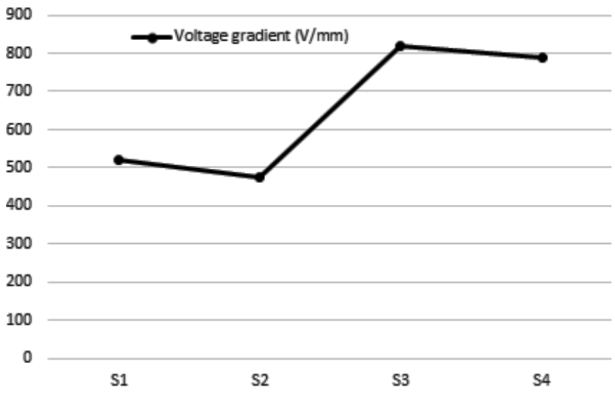

Figure 6. Voltage gradient.

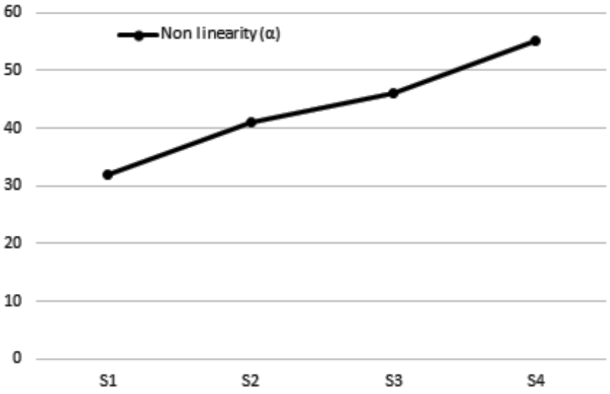

Figure 7. Nonlinear coefficient.

The leakage current of the arrester during normal operating voltage decides its lifespan. This leakage current was computed by applying 0.75 times the breakdown voltage (for S1, 0.75 × 520 V = 390 V, i.e. current while applying 390 V). Figure 8 represent the leakage current of all arrester samples. The leakage currents of the microwave sintered samples are 4.1 μA (S3) and 2.9 μA (S4), which are less compared to conventional sintered samples. Hence, sample S4 may have a better lifespan compared with other samples.

4.3. Capacitance of arrester

It is stated that the capacitance of the arrester block plays a major role during very fast transients [3]. Therefore, the capacitances of all samples were computed using an impedance analyzer with 1 Vrms. Figure 9 represents the capacitances of all the arrester blocks (the values of S1, S2, S3, and S4 are 0.216 nF, 0.183 nF, 0.175 nF, and 0.0985 nF, respectively). Among these samples, S4 shows less capacitance compared with the other samples.

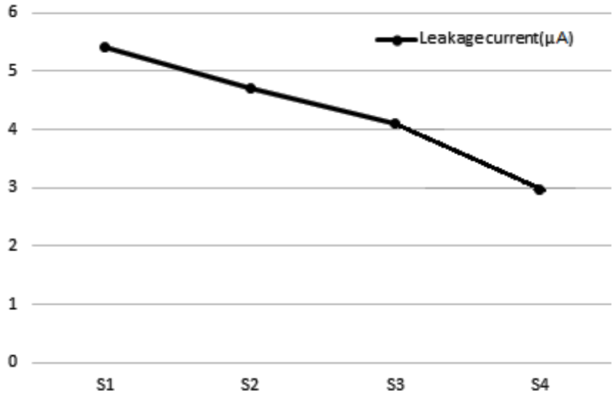

Figure 8. Leakage current.

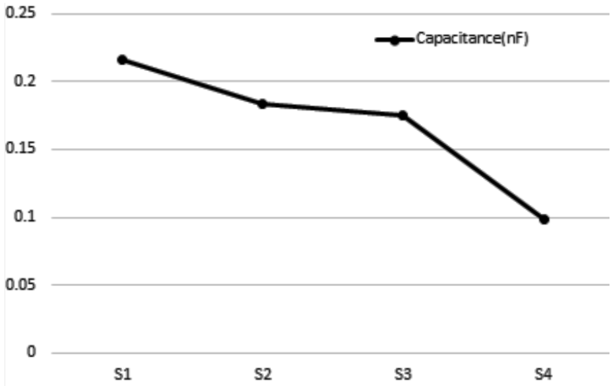

Figure 9. Capacitance of arrester blocks.

When the voltage rating of the arrester is increased, the height of the arrester assembly also increases. It is known that the stray capacitance of an arrester increases with the height of the arrester and this causes a nonuniform potential distribution along the arrester column. Therefore, an arrester block with higher voltage gradient material shortens the height of the arrester column. Consequently, this reduction in height reduces the stray capacitance effect and thereby improves the potential distribution along the arrester.

Among the samples, high gradient samples S3 and S4 can provide a smaller footprint for manufacturing a full arrester assembly, especially for high voltage systems. Subsequently, the height could be reduced by 36% compared with S1 and S2. Consequently, the stray capacitance is condensed along with low block capacitances. With this effect, the initial response of the arrester may be improved and therefore a reduction in the time lag between the peak of residual voltage and current can be achieved. This shows better effectiveness of overvoltage protection. Hence, these samples are more suitable for very fast transients.

5. Summary of results

Four zinc oxide (ZnO) arrester samples were prepared by adding a small ratio of the rare earth element Sc_2O_3 along with the basic composition. The prepared samples were sintered at 1000 °C using conventional and microwave processes for different holding durations. The microstructural and electrical properties of average grain size, density, V-I characteristics, voltage gradient, nonlinear coefficient (α), leakage current, and capacitance of arrester blocks were analyzed with experimental results. Among the different samples, one sample showed better results, which gave an improved voltage gradient (790 V/mm), nonlinear coefficient (55), and leakage current (2.9 μA). The attainment of higher nonlinearity, particularly greater than 50, is a measure of transition speed from insulating to conducting mode (fast response) for better protection of a power system [17,18]. Additionally, less leakage current shows the better lifespan of the arrester. The lowest block capacitance effect of 0.0985 nF at 100 Hz frequency was achieved for the chosen sample. Owing to the lower value of capacitance, the time lag between the peak of residual voltage and discharge current (slow response) is reduced. Therefore, the initial response of the surge arrester against VFTOs can be improved. This inference is supported by Valsalal et al. [5–8], who reported that the time lag depends on arrester capacitance. Based on the above inferences, sample S4 prepared by microwave sintering at a temperature of 1000 °C with 30 min of holding time may be better during VFTOs.

6. Conclusion

Metal oxide arrester samples were prepared with the addition of a rare earth element and sintered at lower temperatures by microwave sintering. Among the prepared samples, one gave a better voltage gradient (790 V/mm), higher nonlinearity (55), the least leakage current (2.9 μA), and reduced capacitance (0.0985 nF at 100 Hz). These values provide a better turnaround pace from capacitive to resistive mode during invasion of fast fronted surges in order to achieve a successful ‘turn on’ of the arrester. Therefore, doping of Sc_2O_3 with the basic composition and with the aid of the microwave sintering effect leads to achieving a high-performance surge arrester for protecting power systems against VFTOs, especially for GISs.

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