A Review of Voltage Distribution on Metal Oxide Surge Arrester and Suggestions for Improvement in High Voltage Applications

Valsalal Prasad, *Member, IEEE*

***Abstract*—Stray capacitive effect of Metal Oxide Surge Arrester (MOSA) may cause non-uniform voltage distribution in both non-conduction and conduction modes. Also, during conduction, there is a delay in operation of arrester, particularly when faced with very fast transient overvoltages (VFTOs). Consequently, there is a necessity to reduce stray capacitive effect for improvement in voltage distribution and reduce delay in response of arrester for VFTOs. One approach is placement of grading rings with appropriate number and size. Numerous researchers have conducted extensive studies on causes of non-uniform voltage distribution, computation of stray capacitances and remedial measures to achieve a more uniform voltage distribution. Further, this investigation holds great significance in polluted environments, damaged arresters and broken sheds, as proper operation of surge arresters relies on environmental conditions, material properties, and shapes of arrester assembly. This paper provides a summary of research conducted by various researchers from the year 1970 and also offers suggestions for further studies of achieving a more uniform voltage distribution and reducing response delay of MOSAs.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9293

***Index Terms*—Block capacitance, Conduction mode, Metal oxide surge arrester (MOSA), Non-conduction mode, Very fast transient overvoltage (VFTO), Stray Capacitance.**

I. Introduction

METAL oxide surge arresters (MOSAs) are composition of various chemicals like zinc oxide, bismuth oxide, cadmium oxide, boron oxide, praseodymium oxide, aluminum oxide and silicon oxide [1], [2]. Zinc oxide remains as dominant element in this composition, accounting for approximately 95-97% of entire resistor with smaller amounts of other metal oxides [3], [4] for controlling non-linearity within the resistor [5] - [11]. The molded arrester blocks are typically stacked within porcelain or polymeric insulators. An equal voltage is to be applied across each block and hence, a linear axial voltage gradient distribution is expected. But, there is a deviation from linear nature because of stray (inherent) capacitance. Since, it varies with height of arrester, the deviation from linear nature is increased with its height, making design of MOSAs as cumbersome [12] - [33]. This stray capacitance (SC) makes non-uniformity of voltage distribution [34] - [36] and is reduced by placing of grading rings with new arrester materials [37] - [44]. This paper summarizes voltage distribution study made on MOSA by different researchers from the year 1970 to till date with a case study.

The associate editor coordinating the review of this manuscript and approving it for publication was Diego Rivelino Espinoza-Trejo (*Corresponding author: Valsalal Prasad*).

Valsalal Prasad is with Department of Electrical and Electronics Engineering, College of Engineering Guindy, Anna University, Chennai, India (e-mail: valsalal@annauniv.edu).

II. Dimension of Single Stack Arrester

The arrester blocks are housed in a hermetically sealed hollow porcelain insulator [30]. Fig. 1 shows arrester blocks and dimension of a single stack (66 kV) arrester.

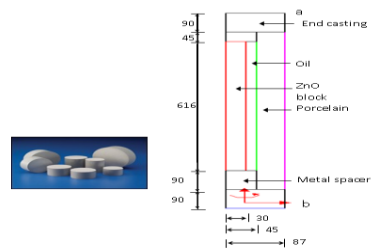


Fig. 1. Arrester blocks and Dimensional details of single stack arrester (mm).

III. Stray Capacitance

It is a capacitive effect between any high voltage point and ground. This is more significant in high voltage MOSAs and is very difficult to measure. In early years, researchers have used approximate empirical formulae for finding stray capacitance by assuming basic electrode shapes [14]. The accurate dimensions are not incorporated in empirical formulae and also for adding grading ring effects, Finite Element Method (FEM) is used for calculating arrester stray capacitance [13], [15], [17], [45], [46]. Electric field around MOSA in both clean and polluted arresters with varying fibre glass thickness and electrodes height sheds are computed [47].

IV. Ill-effects of Arrester Stray Capacitance

The behavior of MOSA depends on distributed stray capacitive effect during both steady state and transient conditions. In non-conduction mode (power frequency voltage), upper portion of blocks are subjected to higher potential gradient since supply voltage is appeared continuously across MOSA. So, higher thermal stresses occur, lead to faster thermal ageing across these stressed blocks with less lifetime [25], [28], [42] - [52]. The voltage non-uniformity during conduction mode (high frequency transient operation) is also more significant with increased steepness of applied current surge [30]. Hence, MOSA behaves as capacitor and inoperative under transients of nanosecond ranges, especially in SF_6 based substation with high voltage rating.

V. Voltage Distribution under Non-conduction Mode

Since leakage current due to resistance is very small, distribution of voltage is calculated only based on arrester capacitances [17], [18], [53]. There are various service conditions like elevated installation, provision of nearby energized apparatus and earthed objects, which may also influence voltage distribution [12]. The key points for this section is summarized in Table I.

Table I
Summarized Key Points for Voltage Distribution

Methods	Findings	Ref
Analytical approach and wireless current	Potential distribution in all conditions	[47], [54], [55]
Electrical field and circuit	Analyzing distribution of potential in arresters	[56]
FEM based analytical method	Solving open boundary axisymmetric electrostatic problems	[57]
FEM based analytical method	3D based potential distribution	[58]
3D FEM and circuit analysis	Potential distribution on 1000 kV gas insulated MOSA	[59]
3D FEM	Comparison of gas insulated MOSAs	[60]
3D FEM	Distribution of potential and stray capacitances	[61] - [64].
FEM	Grading ring optimization	[65]-[67]
Maxwell and EMTP/ATP software	Electric field and leakage current	[68]
FEM	Electric field distribution and optimized grading ring	[69]

Three dimensional design may be used to change geometry or materials for achieving good performance values [25], [26]. There is existing of stray capacitances with high value in SF_6 based MOSA because of earthed metal housing [70], [71]. Here, an attempt is made to compute stray capacitance, Voltage Distribution (VD) for non-conduction and conduction modes and delay in response of arrester for 198 kV arrester as case study. Different arrester ratings, 66 kV (single stack:1×66 kV) to 396 kV (six stacks:6×66 kV) are taken for computing stray capacitance and distribution of voltage.

VI. Stray Capacitance and Distribution of Voltage for Various Heights of MOSA

The stray capacitance and distribution of voltage for different heights are computed using FEM. Table II gives stray capacitance. The voltage in per unit (pu) for single stack (66kV), three stack (198kV) and six stack (396kV) are plotted (Fig.2). There is an increase in non-uniformity of voltage distribution for higher arrester heights. Comparing single stack, six stack arrester is having more non-uniformity.

A. Remedial Measures – Grading rings

Even though many corrective measures are available, one of the methods, generally used for improving voltage non-uniformity is placing of grading rings [72], [73].

Table II
Stray Capacitance - Different Heights of MOSA

kV	Ht (mm)	SC (pF)
66	2116	2.1
132	2732	4.58
198	3348	6.78
264	3964	8.86
330	4580	10.78
396	5196	14.61

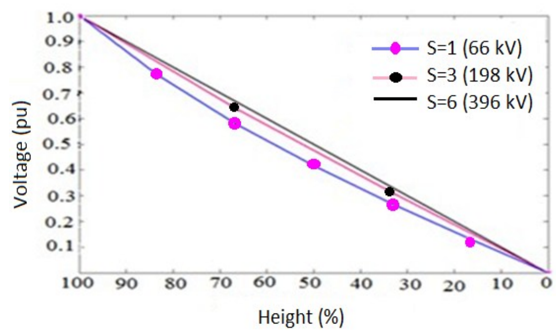


Fig. 2. Voltage Distribution -Various heights (S: no. of stacks).

B. Other Remedial Measures

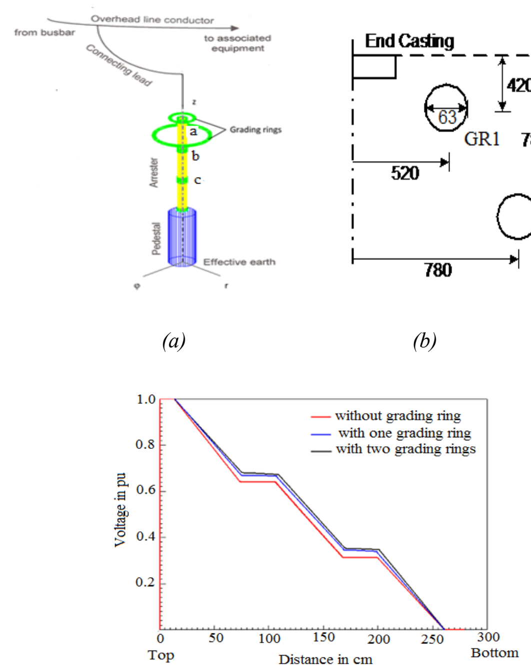
Internal grading circuit, capacitive or resistive elements are employed [15], [17], [18]. This is achieved by placing higher capacitance block at upper portion of arrester and lower capacitance block at bottom portion of arrester. The distribution of voltage is made more uniform on arresters using spacers and Fiberglass Reinforce Plastic (FRP) layers by proper geometries, materials and different surrounding insulation materials [49]. The parallel capacitors are considered to achieve potential distribution coefficient within ±15% [21], [74], [59], but recommended value is less than 5% [61], [62].

C. Case Study for Non-conduction Mode -198kV arrester

An arrester having three stacks with two grading rings, Fig. 3 (a), location of grading rings, Fig. 3 (b) and voltage distribution during non-conduction mode, Fig. 3 (c) are shown. The results are validated with reference [75].

VII. Voltage Distribution under Polluted Environment and Broken Sheds

Non-uniform electric field distribution exists in polluted environmental conditions. The geometry, electrical properties of various components and location of broken shed influence voltage distribution on MOSA [76] - [78]. The arrester housing becomes conducting when it is polluted and redistributes voltage distribution. Generally, resistance of external portion of arrester in clean environmental condition is very high. But, in contaminated conditions, external part of arrester gains some conductivity and hence its resistance decreases. Because of these variations of resistance inside and outside the arrester, distribution of voltage becomes uneven. The arrester blocks undergo an enormous heating resulting as thermal runaway phenomenon. As a consequence, destruction of complete arrester assembly happens. So, successful operation depends on environments. But, mis-operation of arrester on housing is due to dirt or ash from industries, sea salt and sand accumulation. A suggestion is given for revision of ANSI Standard for demonstrating ability of arresters to permit washing while energized [25], [79] - [83].



(a) *(b)*

(c)

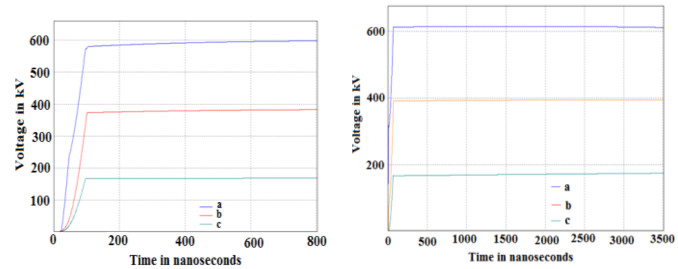
Fig. 3. 3-stack MOSA: (a) Position of grading rings, (b) Dimensions of grading ring in mm, (c) Voltage distribution.

VIII. Voltage Distribution during Conduction Mode

The effect of capacitance during transient mode of arrester is analyzed by computing discharge voltage of arrester with different current surges. The stray capacitance gives considerable effect during nanosecond surges [23]. The electrical stress across upper-most stack of arrester is more during nanoseconds. This stress is increased with higher height or voltage rating of arrester as well as applied current surge with less front time. The increased stress may be reduced by placing suitable number of grading rings in suitable locations. Moreover, arrester with higher gradient material may also reduce height of arrester and hence stray capacitance is reduced. MCOV of arrester:181kV$_{rms}$, discharge voltage: 600kV, discharge current:10kA, non-linear index :50.

A. Case Study for Conduction Mode - 198kV Arrester

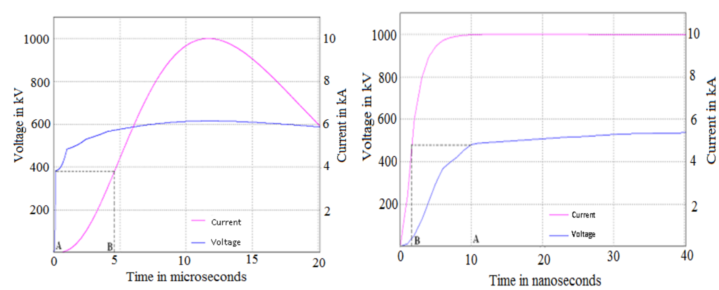
The voltages at various stacks / metal flanges (a, b, c) are simulated with accurately computed stray capacitance for two different current surges as shown in Fig. 4 (a) and Fig. 4(b). There is a non-uniformity in distribution of voltage, which increases for applied current surges with less front time, Fig 4. (b) and is reduced with grading rings in suitable positions.



(a) (b)

Fig. 4. Voltage distribution: (a) During current surge of 10 kA,8/20 µs, (b) During current surge of 10 kA,5ns/10 µs (a, b, c: metal flanges).

When arrester is conducting successfully, its discharge voltage peaks before peak value of applied current surge, shown in Fig.5 (a). When front time of applied current surge is decreased, especially for nanosecond surges, its discharge voltage peaks after occurrence peak of applied current surge, given in Fig. 5 (b). This is because of presence of delay (time lag) in response of arrester. This delay must be reduced for successful conduction of MOSA.



(a) (b)

Fig. 5. Showing delay in response: (a) Conduction of 10 kA,8/20µs current surge, (b) Conduction of 10 kA,5ns/10µs current surge.

B. Placing of Grading Rings

Using details of grading rings, obtained from manufacturer, simulation is carried out for different applied current surges. The voltage appeared across topmost stack is given in Table III.

TABLE III

VOLTAGE ACROSS TOP STACK IN KV

1µs/10µs	5ns/10µs	5ns/10µs (with grading rings)
215.0	219.2	213.8

It is found that, before placing grading rings, when steepness of applied current surge is increased from 1 µs to 5 ns, voltage across top stack is increased from 215.0 kV to 219.2 kV. After placing two grading rings, voltage is reduced from 219.2 kV to 213.8 kV. Even though reduction in non-uniformity is there, this may not be sufficient for successful operation, especially for higher voltage ratings of arrester. Hence another alternative measure is chosen, like addition of new materials.

IX. New Composition of Material

The voltage of about twice that of conventional arrester for rating from 66 kV up to 500 kV with reduced height is obtained by decreasing average grain size of ZnO with a newly added material and improved process of sintering [84] - [90]. The usage of these higher gradient arresters may give flexibility while locating MOSAs in SF_6 based substations [91]- [94]. The conventional arrester elements have lower reference voltage of 200 Volts/mm and could be further increased by 1.5 to 2 times with development of high voltage gradient of 300 Volts/mm [95]. The high voltage gradient (435Volts/mm) arresters could improve distribution of potential along arrester columns by 10% [95] - [97]. The rare earth oxides slow down grain growth because of stabilization of new spinel phases achieved at grain boundary. A uniform high voltage gradient of 600 Volts/mm is developed by controlling grain growth of ZnO with modified process of manufacturing. Doping with rare earth would significantly improve electrical behavior of ZnO arrester blocks like nonlinear coefficient, voltage gradient, and leakage current. The effects of Co_2O_3 on phase composition, electrical behavior, micromorphology and dielectric properties of ZnO blocks are presented [98] - [100]. Hence, leakage current reduction, grain resistivity enhancement and non-linear coefficient improvement in Co-doped ZnO arrester blocks are understood. Finally, there is reduction of grain size, height and compactness of arrester with improvement of distribution of voltage in both steady and transient states of power system [39], [101] - [103].

X. Shortening of Arrester Columns using High Gradient Material – Scandium Oxide

The operational time delay between arrester discharge voltage and current is minimized by reducing arrester capacitive effect with reduction of height of arrester column. The ZnO (MOSA) arrester with high voltage gradient material plus Rare Earth (RE) additives shortens length of arrester and also RE elements bring better results when used with $ZnO-Bi_2O_3$ based arrester materials. A few selected RE additives like Sc_2O_3, Yb_2O_3, Y_2O_3, Er_2O_3 and Dy_2O_3 have features to improve arrester performance. Among them, Sc_2O_3 is found to be the best suited to effect the required higher arrester voltage gradient. On mixing it with other arrester basic ingredients, a better control over grain growth during sintering process is established. This control is considered as a factor to bring a strong pinning effect and reduced grain sizes. Further, addition of Sc_2O_3 enhances grain boundaries and increases possibility of getting material of better potential gradient for blocks of MOSA. The blocks of surge arrester are prepared with reagent raw materials, ZnO in major proportion and a small quantum of Bismuth (III) Oxide, Antimony (III) Oxide, Cobalt (III) Oxide, Chromium (III) Oxide, Manganese dioxide, and Scandium (III) Oxide. The required weighed powders are put in a nylon jar having zirconia balls. Ball milling method is carried out with a wetting agent. The ratio of powder to balls is taken as 1:10. This process is done for ten hours. For two hours, the taken powders are heated at 600°C. Using Agate/mortar, the heated powders are pulverized after adding 2wt% of Poly Vinyl Alcohol. Then the powders are crystallized into grains by sieving through a 100 mesh screen. Now, in a die, the prepared powder is placed and then in a uniaxial pressing machine. Afterwards, this is pressed. A pressure of 150Mpa is applied for making the powders in to discs. A density of about 55% of its theoretical density is found for wet / green cylindrical arrester. Now the arrester disc is ready for process of sintering. The arrester sample is subjected to various required processes of sintering. Finally, required dimensions of arrester samples are obtained after employing lapping and grinding machines. Now the entire process is completed for making an arrester block. The resultant block takes the shape of an innovative new composition arrester blocks. For conventional arrester disc, voltage gradient is in the range of 475-520Volts/mm and method currently in practice brings non-uniform heating effect. Moreover, there are higher height of arrester columns and more capacitance effect. Hence, performance under all types of VFTOs are not at the desired level. For genetically modified ZnO arrester disc (addition of RE viz., Sc_2O_3), voltage gradient is to achieve higher voltage gradient of maximum value of 825Volts/mm. Microwave sintering produces uniform heating with the attendant higher densification of arrester discs by reduced holding duration for the disc, which brings higher breakdown fields. The height of arrester is low and hence performance under all types of VFTOs are exceedingly good. The microstructures of conventional and new composition arresters reveal that there is a lower value in grain sizes, a higher value in voltage gradients and reduced height requirement per unit for genetically modified arresters. Consequently, the newly developed ZnO surge arrester with high-gradient materials enhances its behavior and improves voltage distribution by mitigating stray capacitance effect through reduced height.

XI. Future Research

Finite element methods and intelligent techniques are used for computing stray capacitance and voltage distribution of arresters. The stray capacitance is increased with height of MOSA column, but its reduction is achieved with new dimensions of grading rings and different composition of materials with suitable manufacturing process. Rare earth elements are very suitable for obtaining required higher voltage gradient arrester. Scandium Oxide is one among them, which enhances grain boundaries and increase possibility of formation of improved value of voltage gradient material for arrester, hence there is a reduction of length or height of arrester. The distribution of voltage across SF_6 based MOSA is more uniform as compared to conventional MOSAs because of increased stray capacitances resulted from grounded metallic enclosure. Gas insulated arrester of ratings, above 245kV are in practice and hence, further studies on these arresters are very much essential in future with good design of grading rings. Also as future work, it is suggested that new materials, like Scandium Oxide may be used for further reduction of height of arrester. So, fabrication of genetically modified MOSAs (modified ZnO arrester) with innovative fabrication techniques and sintering process may help in bringing an effective MOSA under all VFTOs.

XII. Conclusions

This paper discusses an extensive review made on voltage distribution of arresters from the year 1970 (5+ decades). Researchers have found that there is non-uniformity of distribution of voltage along height of arresters during their steady and transient states of operation due to stray capacitance.

Few remedial measures, like placing grading rings and connecting series capacitors, have been described to make voltage distribution more uniform. A case study is used to compute capacitance and distribution of voltage using FEM. There is a reduction of non-uniformity of voltage distribution after placing grading rings. The suggested measures may not be sufficient to make required uniformity since voltage level of power systems are increasing day by day. Finally, it is observed from reported work and case study that non-uniformity of voltage distribution decreases significantly with reducing height of arrester, which is achieved with material of higher voltage gradient. In future, preparation of new high gradient arrester material would be a suitable method for achieving reduced height of arrester with excellent non-linear as well as electrical characteristics. The same voltage distribution study may be carried out in polluted environments, damaged arresters and broken sheds. The modifications in arrester are having effect under both steady and transient states of operation.

References

[1] M.R.Meshkatoddini, " Investigation of the influence of the ZnO varistor preparation method on its characteristics", *Conference Record of the 2008 IEEE International Symposium on Electrical Insulation*, pp. 320-323, 2008. doi:10.1109/ELINSL.2008.4570338

[2] Karim ANM, Shahida Begum, "Enhanced performance of zinc oxide arrester by simple modification in processing and design", *Journal of Material Science and Engineering*, vol.3, Iss.1, pp. 1-6, 2014. doi: 10.4172/2169-0022.1000135

[3] Adrian Constantin Paun, Doru Vatau, Flaviu Mihai, Florin Ionel Balcu, "New Manufacturing Process for the Metal Oxide Varistors used on Low Voltage Surge-Arresters", *18th International Scientific Conference on Electric Power Engineering*, 2017. doi:10.1109/EPE.2017.7967318.

[4] Mihaela Frigura-Iliiasa, Florin Solomonesc, Flaviu M. Frigura-Iliasa, Petru Andea, "A few aspects concerning a new varistor material for low and medium voltage surge arresters", *45th International Universities Power Engineering Conference UPEC 2010*.

[5] Marek Olesz, Leszek S. Litzbarski, Grzegorz Redlarski, "Leakage current measurements of surge arresters", *Energies* 16, 6480, 2023. doi:10.3390/en16186480

[6] Cosmin Rimescu, Emil Lazarescu, Flaviu M. Frigura-Iliasa, Lia Dolga, Hannelore E. Filipescu, "Study about some Two Main Dopants for a ZnO based Varistor Material with 5 Additives, Applied in Overvoltage Protection Equipment", *19th International Scientific Conference on Electric Power Engineering,* 2018. doi:10.1109/EPE.2018.8395942.

[7] Welson Bassi, Hédio Tatizawa, "Early Prediction of Surge Arrester Failures by Dielectric Characterization", *IEEE Electrical Insulation Magazine*, vol, 32, no.2, pp. 35-42, 2016. doi:10.1109/MEI.2016.7414229.

[8] Elvis Alexandru Dogaru, Adrian Augustin Pocola, Mihaela Frigura-Iliasa, Flaviu Mihai Frigura-Iliasa, "The Influence of Two Main Doppants on the Electrical Properties of Metal Oxide Varistors", *10th International Conference on Energy and Environment*, 2021. doi:10.1109/CIEM52821.2021.9614753.

[9] Pengfei Meng, Yao Zhou, Jinbo Wu, Jun Hu, Jinliang He, "Novel ZnO Varistors for Dramatically Improving Protective Effect of Surge Arresters", *34th International Conference on Lightning Protection*, 2018. doi: 10.1109/ICLP.2018.8503330.

[10] Pengfei Meng, Wei Cao, Chao Chen, Shuai Wan, Heng Xu, Jun Hu, Jinliang He, "Excellent electrical properties of zinc-oxide varistors by tailoring sintering process for optimizing line-arrester configuration", *IEEE International Conference on High Voltage Engineering and Application*, 2020. doi: 10.1109/ICHVE49031.2020.9279439.

[11] Razvan Petrenci, Mihaela Frigura-Iliasa, Flaviu Mihai Frigura-Iliasa, Marius Mirica, Florin Balcu, "Experimental Study about the Sintering Temperature of a New Metal Oxide Varistor Material", *10th International Conference on Electrical and Electronics Engineering,* pp.398-401, 2017.

[12] N.Alame, Melik G, "Axial voltage and gradient distribution of metal oxide surge arresters", *Proceedings of 3rd International Conference on Properties and Applications of Dielectric Materials*, 1991, pp.1149-1151.

[13] Z.J Csendes, J.R Hamann, "Surge arrester voltage distribution analysis by the finite element method", *IEEE Trans. Power App Syst*. vol. 100, no.4, pp. 1806-1813, 1981

[14] P Sarma Maruvada, N. Hylten-Cavallius, "Capacitance calculations for some basic high voltage electrode configurations", *IEEE Trans. Power App Syst.,* vol. 94, no. 5, pp. 1708-1713, 1975.

[15] M. Oyama, I.Oshima, M.Honda, M.Yamashita, S.Kojima, "Analytical and experimental approach to the voltage distribution on gapless zinc oxide surge arresters", *IEEE Trans. Power App Syst.,*vol.100, no. 11 pp. 4621-4627, 1981

[16] E.G.Maier, R.M.Rudolph, W.Schmidt, F.Hunziker, "Voltage distribution and pollution performance of metal oxide arresters", *CIGRE* 33-12, pp. 1-7, 1986.

[17] A.Haddad, P.Naylor, "Finite element computation of capacitance networks in multiple electrode systems: application to ZnO surge arresters", *IEE Proceedings of Sci. Meas. Technol*.,vol.145, no. 4, pp. 129-135, 1998

[18] Liu Xuezhong, Liu Fuyi, "The influence of varistor disk capacitance of MOV arrester on its voltage distribution", *Proceedings of 6th International Conference on properties and applications of dielectric materials*, vol 2, pp 761-764, 2000.

[19] S.N.Fernando, M.R.Raghuveer, "Simulation of metal oxide arrester diagnostics including stray capacitance effect", *12th International Symposium on high voltage engineering*, 5-51, pp. 771-773, 2001.

[20] U.Kumar, V.Mogaveera, "Voltage distribution studies on ZnO arresters", *IEE Proceedings of Gener. Transm. Distrib.*, vol. 149, no. 4, pp.457-462, 2002. doi:10.1049/ip-gtd:20020346

[21] Jinliang He, Jun Hu, Shanqiang Gu, Bo Zhang, and Rong Zeng, "Analysis and Improvement of Potential Distribution of 1000-kV Ultra-High-Voltage Metal–Oxide Arrester", *IEEE Trans Power Deliv*., vol. 24, no.3, 1225-1233, 2009. doi:10.1109/TPWRD.2009.2014034

[22] R.Karthik, "A Novel analysis of voltage distribution in zinc oxide arrester using finite element method", *International Journal of Recent Trends in Engineering and Technology*, vol.1, no. 4, pp. 1-3, 2009. doi: 01. IJRTET.01.04.39

[23] P.Valsalal, S.Usa, K.Udayakumar, "Effect of Stray Capacitance on Surge Arrester Performance", *Proceedings of the World Congress on Engineering and Computer Science WCECS, vol. I,* 2009. ISBN:978-988-17012-6-8

[24] Huijia Liu, Yunxiang Liu, "Modeling and Simulation of MOSA Including Stray Capacitance to the ground", *Asia-Pacific power and Energy Engineering Conference*, 2012.

[25] Christos A. Christodoulou, Vasiliki Vita, Valeri Mladenov, Lambros Ekonomou, "On the Computation of the Voltage Distribution along the Non-Linear Resistor of Gapless Metal Oxide Surge Arresters", *Energies*, vol. 11 (3046) 1-14, 2018. doi:10.3390/en11113046

[26] Syahirah Abd Halim, Azah Mohamed, Nor Azwan Mohamed Kamari, Afida Ayob, Ab Halim Abu Bakar, Hazlee Azil Illias, "Optimization of zinc oxide arrester design using gravitational search algorithm and imperialist competitive algorithm",

Indonesian Journal of Electrical Engineering and Computer Science, vol. 13, no. 3, pp. 853-860, 2019. doi: 10.11591/ijeecs. v13.i3. pp853-860

[27] Pengfei Meng, Xiaolei Zhao, Xiao Yang, Shuai Wan, Heng Xu, Jun Hu, Jinliang He, "High voltage gradient zinc oxide varistors for line surge arresters and GIS tank-type arresters", *The 11th Asia-Pacific International Conference on Lightning*, 2019.

[28] Nadjim Alti, Abdelhafid Bayadi, Khaled Belhouchet, "Grading ring parameters optimization for 220 kV metal-oxide arrester using 3D-FEM method and bat algorithm", *IET Sci Meas. & Technol*. vol. 15, pp. 14-24, 2020. doi: 10.1049/smt2.12002

[29] Alessandro Mingotti, Federica Costa, Lorenzo Peretto, Roberto Tinarelli, Paolo Mazza, "Modeling Stray Capacitances of High-Voltage Capacitive Dividers for Conventional Measurement Setups", *Energies*, vol. 14, (1262), pp. 1-14, 2021. doi.org/10.3390/en14051262

[30] P.Valsalal, S.Usa, K.Udayakumar, "Modelling of metal oxide arrester for very fast transients", *IET Sci Meas & Technol*., vol.5, no.4, pp. 140-146, 2011.doi: 10.1049/iet-smt.2010.0129

[31] Krystian Leonard Chrzan, Jaroslaw Gielniak, "Voltage distribution along metal oxide surge arresters", *XIIIth International Symposium on High Voltage Engineering*, Netherlands, pp. 1-4, 2003. ISBN 90-77017-79-8.

[32] J. Araya, J. Montaña, R. Schurch, "Electric Field Distribution and Leakage Currents in Glass Insulator Under Different Altitudes and Pollutions Conditions using FEM Simulations", *IEEE Latin America Transactions*, Vol. 19, No. 8, pp. 1278 – 1285, 2021.

[33] Behnam Ranjbar, Ali Darvishi, Rahman Dashti, Hamid Reza Shaker, "A Survey of Diagnostic and Condition Monitoring of Metal Oxide Surge Arrester in the Power Distribution Network" *Energies*, 15, 8091, 2022. doi:org/10.3390/en15218091.

[34] Lulu Wang, Ke Wan, Li Chen, Qingchun Qian, Jiarui Huang, "Analysis about potential distribution of the Ur 780kV metal-oxide surge arrester for 1000kV substation" *4th IEEE Conference on Energy Internet and energy system integration,* pp. 1125-1130, 2020. doi:10.1109/EI250167.2020.9346864.

[35] LI Shan, JIN Ming, "Analysis and treatment of shunt Capacitance defect of 750 kV metal oxide arrester", *4th Asia Energy and Electrical Engineering Symposium,* pp. 940-944, 2022. doi:10.1109/AEEES54426.2022.9759763

[36] S. T. Li, J. Q. He, J. J. Lin, H. Wang, W. F. Liu, L. Liao, "Electrical-thermal failure of metal–oxide arrester by successive impulses", *IEEE Trans Power Deliv*., vol. 31, no. 6, pp. 2538-2545, 2016. doi: 0.1109/TPWRD.2015.2506785

[37] P.Valsalal, S.Usa, K.Udayakumar, "Response of metal oxide arrester in gas insulated substation and methods to improve its dynamic characteristics", *IET Sci Meas & Technol*., vol. 6, no.4, pp. 222-228, 2012. doi: 10.1049/iet-smt.2011.0051

[38] Valsalal Prasad, "Possible Measures to Enhance the Performance of Metal–Oxide Arresters in the EHV Network Under Very Fast Transients", *IEEE Trans Power Deliv*., Vol. 30, no. 2, pp. 783-790, 2015. doi: 10.1109/TPWRD.2014.2346533

[39] Kannadasan Raju, Valsalal Prasad, Rajvikram Madurai Elavarasan, Umashankar Subramaniam, Dhafer J. Almakhles, "Development of High Gradient ZnO Arrester Material for High Voltage Applications", *IEEE Access*, vol. 8, pp. 115685-115893, 2020. doi:10.1109/ACCESS.2020.3003817

[40] Tom Bialek, Insulation system protection with zinc oxide surge arresters, *IEEE Electr. Insul Magazine*, 15 (1) (1999) 5-10.doi:10.1109/57.744584

[41] Yvonne Spack-Leigsnering, Erion Gjonaj, Herbert de Gersem, "Electrothermal Optimization of Field Grading Systems of Station Class Surge Arresters" *IEEE Journal on multiscale and multiphysics computational techniques*, vol. 4, pp.29-36, 2019. doi: 10.1109/JMMCT.2019.2896630.

[42] Vishal V.Waghmare, Vinay Kumar Yadav, Ishan M. Desai, "Optimization of Grading Ring of Surge arrester by using FEM method, PSO & BAT Algorithm", *2nd International Conference on Advance Computing and Innovative Technologies in Engineering, ICACITE*, pp. 367-370, 2022

[43] Grupesh Tapiawala, Subhankar Das, Atadal Dash, Kirusnaraj, Kumar Virvani, "Space Optimization for high voltage surge arrester", *15th (IEEE) International Conference on Industrial and Information Systems*, pp.50-53, 2020. doi:10.1109/ICIIS51140.2020.9342657

[44] M.R. Aghaebrahimi, R. Shariatinasab, M. Ghayedi, "Optimal design of grading ring of surge arresters due to electric field distribution", *16th IEEE Mediterranean Electrotechnical Conference*, pp.548-550, 2012. doi:10.1109/MELCON.2012.6196493

[45] Mihir N. Velani, Santosh C. Vora, "Stability predictions of zinc oxide surge arrester by employing finite element solutions", *International Conference on High Voltage Engineering and Technology*, 2019. doi: 10.1109/ICHVET.2019.8724129.

[46] Kalaiselvi Aramugam, Hazlee Azil Illias, Yern Chee Ching, Mohd Syukri Ali,Mohamad Zul Hilmey Makmud, "Optimal design of corona ring for 132 kV insulator at high voltage transmission lines based on optimisation techniques" *Energies* 16, 778, 2023.doi:org/10.3390/en16020778

[47] Vasiliki Vitaa, Christos A. Christodoulou, "Comparison of ANN and finite element analysis simulation software for the calculation of the electric field around metal oxide surge arresters", *Electr. Power Syst. Res*. Vol. 133, pp. 87–92, 2016. doi.org/10.1016/j.epsr.2015.11.041

[48] S. Kojima, M.Oyama, M.Yamashita, "Potential distributions of metal oxide arresters under various environmental conditions", *IEEE Trans Power Deliv*. Vol. 3, no. 3, pp. 984-989, 1988.

[49] M.R. Aghaebrahimi, M. Ghayedi, R. Shariatinasab, R. Gholami, "A more uniform electric field distribution on surge arresters through the optimal design of spacer and fiber glass layer", *Research Journal of Applied Sciences, Engineering and Technology*, vol. 5, no. 13, pp. 3604–3609, 2013.

[50] Suat ILHAN, Aytug FONT, Ozcan KALENDERLI, " Numerical Analysis of a Metal-Oxide Surge Arrester by using Finite Element Method", *International Conference on High Voltage Engineering and Application*, 2016. doi:10.1109/ICHVE.2016.7800720.

[51] Hazlee Azil Illias, Chea Zern Hong, Kalaiselvi Aramugam, Hazlie Mokhlis, Azrul Mohd Ariffin, Mohd Fairouz Mohd Yousof, "Optimization of grading ring design for metal oxide arrester using gravitational search algorithm",*13th International Conference on the Properties and Applications of Dielectric Materials*, 2021. doi:10.1109/ICPADM49635.2021.9493910

[52] Hazlee Azil Illias, Syahirah Abd Halim, Ab Halim Abu Barkar, Hazlie Mokhlis, "Determination of surge arrester discharge energy using finite element analysis method" *IET Sci Meas. & Technol*. vol. 9, pp. 693-701, 2015. doi: 10.1049/iet-smt.2014.0240

[53] Jun Hu, Shanqiang Gu, Zhifei Han, Guangzhao Yang, Wei Cao, "Research on improving electric field distribution of UHV DC line arrester", *IEEE International Conference on High Voltage Engineering and Application,* 2020. doi:10.1109/ICHVE49031.2020.9280023

[54] Dantian Zhong, Qiang Gao, Maojun Wang, Qi Liu, Feng Yuan, Guangming Zhang, Yue Han, Lin Shi, Peixian Cong, "Based on the wireless-current method for measurement and test analysis of oxide arrester potential distribution*", 4th International Conference on Modeling and Simulation,* pp. 33-38, 2015. doi:10.1109/MAS.2015.18.

[55] Shiyi Zhou, Haoran Wang, Huidong Tian, Zehua Wu, Jianwei Cheng, Peng Liu, Zongren Peng, " Transient electric field

calculation of Zinc oxide arrester under lightning impulse Voltage", *IEEE Conference on Electrical Insulation and Dielectric Phenomena*, pp. 231- 234, 2018. doi: 10.1109/CEIDP.2018.8544771.

[56] Jinliang He, Rong Zeng, Shuiming Chen, Zhicheng Guan, "Potential distribution analysis of suspended-type Metal-oxide surge arresters", *IEEE Trans Power Deliv*., vol. 18, no. 4, pp. 1214-1220, 2003. doi: 10.1109/TPWRD.2003.817494

[57] S. J. Han, J. Zou, S. Q. Gu, J. L. He, J. S. Yuan, "Calculation of the Potential Distribution of High Voltage Metal Oxide Arrester by Using an Improved Semi-Analytic Finite Element Method", *IEEE Trans Magnetics*, vol. 41, no. 5, pp. 1392-1395, 2005. doi: 10.1109/TMAG.2005.844350

[58] Shejiao Han, Shanqiang Gu , Jinliang He , Yanfeng Lu, Yiping Han, "3D Electric Calculation for a Station Class ZnO Surge Arrester for 1100kV Substation Using the Hybrid Finite Element-Analytical Approach", *12th Biennial IEEE Conference on Electromagnetic Field Computation*, pp.4, 2006. doi:10.1109/TMAG.2005.844350

[59] Bowen Meng, Bo Zhang, Jinliang He, "Potential Distribution Analysis and Improvement of 1000 kV Gas Insulted Switch Metal Oxide Arrester", *Proceeding of International Conference on Electrical Machines and Systems*, pp. 1321-1326, 2007.

[60] Bo Zhang, Jinliang He, "Influence of Grading Ring on Potential Distribution of 1000 kV Gas Insulted Switchgear Metal Oxide Arrester", *International Conference on High Voltage Engineering and Application*, pp.379-382, 2008. doi: 10.1109/ICHVE.2008.4773952

[61] Jinliang He, Jun Hu, Bo Zhang, "Grading Structure Design of Surge Arrester for 1000- kV Ultra-High Voltage Air-insulated Substation", *International Conference on High Voltage Engineering and Application*, pp. 84-87, 2008.

[62] J.He, H.Jun, M. BoWen, Z.Bo, Z.Bin, C. ShuiMing, Z.Rong, "Requirement of ultra-high voltage GIS arrester to voltage gradient of metal-oxide varistor", *Science in China Series E: Technological Sciences*, vol. 52, no. 2, pp. 450–455. 2009

[63] Wang Chuang, Liu Peng, Peng Zongren, "Voltage-Sharing performance of MOA for l000kV UHV GIS", *Proceedings of 9th International Conference on Properties and Applications of Dielectric Materials*, K-17, pp.1184-1187, 2009

[64] C.A. Spanias, C.A. Christodoulou, I.F. Gonos, I.A. Stathopulos, "Electric Field Measurements around a Metal Oxide Surge Arrester", *International Conference on High Voltage Engineering and Application*, pp. 278- 281, 2010.

[65] Saravanan Selvaraj, Nitin Jha, D. John Yesuraj, "Analysis of potential distribution of 1200kV ultra-high voltage lightning arrester", *Eight International Conference on Switchgear & Controlgear, (Emerging Trends in Switchgear)*, 2011.

[66] M. Kanya Kumari, R.S. Shivakumara Aradhya, B. Rajaiyya, S. Kondalarao, "Design of grading ring for 624kV gapless zinc oxide surge arrester", *IEEE 10th International Conference on the Properties and Applications of Dielectric Materials*, 2012.

[67] Saravanan Selvaraj, Nitin Jha, D. John Yesuraj, "Voltage Distribution Studies on Ultra-High Voltage Lightning Arrester", *CIGRE, Session 2.2 Equipment*, pp 1-8, 2013.

[68] M. Khodsuz, M. Mirzaie, "Analysis of grading ring design parameters and heat sink numbers effect on voltage distribution and leakage current in metal oxide surge arrester", *Iranian Journal of Electrical and Electronic Engineering*, vol. 10, no. 2, pp. 152-158, 2014.

[69] Chao Zhang, Jeffrey J. Kester, Charles W. Daley, Stephen J. Rigby, "Electric field analysis of high voltage apparatus using finite element method", *Annual Report Conference on Electrical Insulation and Dielectric Phenomena,* 2010. doi:10.1109/CEIDP.2010.5723955

[70] M. Mohana Rao, Archana Lanjewar, Neelam Tiwari, "Analytical and experimental studies on 245 kV gas insulated surge arrester", *Electr. Power Syst. Res.* 204, 107713, pp. 1-9, 2022. doi:10.1016/j.epsr.2021.107713

[71] R. Gohler, L. Klingbeil, "Special Requirements on Gas-Insulated, Metal-Oxide Surge Arresters", *International Conference on Power System Technology*, pp 1-6, 2006

[72] Laura A. M. D'Angelo, Yvonne Späck-Leigsnering, Herbert De Gersem, "Electroquasistatic quasi-3D finite element simulation of a graded surge arrester", *Wiley,* pp. 1-13, 2019. doi: 10.1002/jnm.2575.

[73] Yvonne Späck-Leigsnering, Maren Greta Ruppert, Erion Gjonaj, Herbert De Gersem, Volker Hinrichsen, " Simulation analysis of critical parameters for thermal stability of surge arresters", *IEEE Trans Power Deliv,* 37 (2) (2022) 871–879.

[74] Hans Sjöstedt, Lennart Stenström, David Pusch, Jörg Ostrowski, "Voltage grading design of UHV surge arresters using 3D transient capacitive-resistive field simulations", *International Conference on High Voltage Engineering and Application*, pp. 32-35, 2010. doi:10.1109/ICHVE.2010.5640871.

[75] Amandeep Kaur, Harveer Singh, "Utilizing the Fem Approach, PSO, and Firefly Algorithm, Surge Wire Grades Ring Modification was Achieved, "*11th International Conference on System Modeling & Advancement in Research Trends*", pp. 655-659, 2022. doi:10.1109/SMART55829.2022.10047026.

[76] K. Feser, W.Kohler, D.Qiu, K.Chrzan, "Behaviour of zinc oxide surge arrester under pollution", *IEEE Trans Power Deliv*., vol. 6, no. 2, pp. 688-695, 1991.

[77] B. Vahidi, R. Shariati Nassab, J. Sh. Moghani, S. H. Hosseinian, "Electric field and voltage distribution on ZnO surge arrester", *IEEE Region 10 Conference TENCON 24*, pp. 367-368, 2004.

[78] B. Vahidi, R. Shariati Nasab, J. Sh.Moghani, S. A. Kashi, S. h. Hosseinian, "Three Dimensional Analyses of Electric Field and Voltage Distribution on ZnO Surge Arrester with Broken Sheds", *IEEE/PES Transmission and Distribution Conference & Exhibition*, pp. 1-2, 2005

[79] F. Tighilt, A. Bayadi, A. Manu. Haddad, "Voltage Distribution on ZnO Polymeric Arrester Under Pollution Conditions", *45th International Universities Power Engineering Conference UPEC*, 2010.

[80] Ferhat Tighilt, "Voltage Distribution Studies in Polluted ZnO Arrester Using the FEMLAB", *Advanced Materials Research, Trans Tech Publications*, 268-270, 412-417, 2011. doi:10.4028/www.scientific.net/AMR.268-270.412

[81] Mihir N.Velani, " A Comparative Analysis of Metal-Oxide Surge Arrester", *International Conference on Energy, Communication, Data Analytics and Soft Computing*, pp. 2083-2085, 2017. doi: 10.1109/ICECDS.2017.8389816.

[82] Pipei ZHANG, Wei SHI, Jie LI, Jingwen SUN, "Simulation of Radial Electric Field and Voltage Distribution of 500kV MOA Under Different Conditions of Pollution", *5th Asia Conference on Power and Electrical Engineering*, pp. 272- 276, 2020.

[83] E.C.Sakshaug, J.S. Kresge, D.A. Mark, G.G. Karady, "Contamination & hot wash performance of zinc oxide station arresters", *IEEE Trans. Power App Syst.*, vol. 101, no. 5, pp. 1095-1104, 1982.

[84] Siyuan Cheng, Manling Dong, Xi Shi, Lei Guo, Wei Yao, Wei Wang, Yunrui Ma, "Influence of Sintering Temperature on the Microstructure and Properties of ZnO Varistor Ceramics Prepared by Chemical Precipitation Method" *IEEE International Conference on Power Systems and Electrical Technology*, pp. 121-126, 2022. doi: 10.1109/PSET56192.2022.10100522.

[85] Pengkang Xie, Jianping Hu, "Influence of sintering temperature and ZrO2 dopants on the microstructure and electrical properties of zinc oxide varistors", *IEEE Access*, Vol. 7, pp. 140126 – 140133, 2019. doi:10.1109/ACCESS.2019.2941965.

[86] Mitsunori Hama, Hideaki Ishizaka, Junichi Shimizu, Susumu Nishiki, Isao Kaku, "Development of advanced built-in surge arresters for distribution system with new zinc–oxide elements", *IEEE Trans Power Deliv*., vol. 16, no. 4, pp. 576-581, 2001
[87] L. Stenstrom, J. Taylor, H. Westerlund, "An optimal surge arrester for EHV air insulated stations utilizing high-gradient MO resistors", *Electrical Insulation Conference*, pp. 201-205, 2013. doi:10.1109/EIC.2013.6554233
[88] Wangcheng LONG, Jun HU, Jun LIU, Jinliang HE, Fengchao LUO, "Dielectric spectroscopies of ZnO Varistors with high voltage gradient under surge aging condition", *Proceedings of the 9th International Conference on Properties and Applications of Dielectric Materials*, pp. 289-292, 2009. doi: 10.1109/ICPADM.2009.5252429
[89] Wei CAO, Zihao LIU, Xiumin CHEN, Shanqiang GU, Shuai WAN, Yueting ZHU, "Development and application of the high-gradient zinc oxide varistor", *35th International Conference on Lightning Protection and XVI International Symposium on Lightning Protection*,2021. doi:10.1109/ICLPandSIPDA54065.2021.9627350
[90] Hao Wang, Hongfeng Zhao, Wenxin Liang, Shaohua Fan, Jiashuang Kang, "Effect of sintering process on the electrical properties and microstructure of Ca-doped ZnO varistor ceramics", *Materials Science in Semiconductor Processing,* 133 (2021) 105880. doi:10.1016/j.mssp.2021.105880
[91] T.Imai, T.Udagawa, H. Ando, Y.Tanno, Y.Kayano, M.Kan, "Development of high gradient zinc oxide nonlinear resistors and their application to surge arresters"', *IEEE Trans Power Deliv*., vol. 13, no. 4, 1182–1187, 1998.
[92] S.Shichimiya, M.Yamaguchi, N.Furuse, M.Kobayashi, S.Ishibe, "Development of advanced arresters for GIS with new zinc-oxide elements", *IEEE Trans Power Deliv*., vol. 13, no. 2, pp. 465–471, 1998.
[93] S.Shirakawa, I.Ejiri, S.Watahiki, S.Kondo, "Application of high voltage gradient zinc oxide elements to SF_6 gas insulated surge arresters for 22 kV-765 kV power systems", *IEEE Trans Power Deliv*., vol. 14, no. 2, pp. 419–424, 1999.
[94] Kang Hui, Cenyue Gao, Yuhao Chen, Yanzhao Xie, Shuang Tian, "Research on iterative method for the potential distribution calculation of arrester", *The 5th International Conference on Power and Energy Technology*, pp. 503-507, 2023. doi: 10.1109/ICPET59380.2023.10367691.
[95] S.Shirakawa, S.Yamada S.Tanaka, I.Ejiri, S.Watahiki, S. Kondo, "Improved zinc oxide surge arresters using high voltage gradient 300 V/mm, 400 V/mm ZnO elements", *IEEE Trans Power Deliv*., vol. 15, no. 2, pp. 569–574, 2000.
[96] JinLiang, HE, Jun, HU & YuanHua, LIN, "ZnO varistors with high voltage gradient and low leakage current by doping rare-earth oxide", *Science in China Series. E-Technological Science*, vol. 51, no. 6, pp. 693-701, 2008. doi: 10.1007/s11431-008-0085-x
[97] T.Fukano, M.Mizutani, Y.Kayano, Y.Kasuga, H.Andoh, "Development of GIS type surge arrester applying Ultra high voltage gradient ZnO element", *IEEE PES, Transmission and Distribution Conference and Exposition*, pp. 1-5, 2012.
[98] F.Jiang, Z.Peng, Y.Zang, X.Fu, "Progress on rare-earth doped ZnO-based varistor materials", *Journal of Advanced Ceramics*, vol. 2, no. 3, pp. 201–212, 2013. doi: 10.1007/s40145-013-0071-z
[99] Jun Hu, Jinliang He, Qingheng Chen, "High Voltage Gradient ZnO nonlinear resistor doped with rare-earth oxide", *IEEE 8th International Conference on Properties & applications of Dielectric Materials*, pp. 963-966, 2006. doi: 10.1109/ICPADM.2006.284338.
[100] Men Guo, Yao Wang, Kangning Wu, Lei Zhang, Xia Zhao, Ying Lin, Jianying Li, "Revisiting the effects of Co2O3 on multiscale defect structures and relevant electrical properties in ZnO varistors", *IET High Voltage*, vol. 5, no.3, pp. 241-248, 2020.doi: 10.1049/hve.2019.0419
[101] S. S. Kim, H. G. Cho, I. S. Choi, T. G. Park, C. H. Park, S. Y. Jung, "A study on the microstructure and surge characteristics of ZnO varistor for distribution arrester" pp. 2212-2217, 2002
[102] Siyuan Liu, Liudan Wang, Shiyu Liu, Zhiyuan Liu, Yingsan Geng, "Modeling and Experimental Validation on Current Uniformity Characteristics of Parallel Spiral Structure Surge Arrester in ±550 kV DC GIS", *Applied Sciences*, 14, 5744, pp. 1-19, 2024. doi:10.3390/app14135744
[103] R. Kannadasan, P.Valsalal, R.Jayavel, "Performance of metal oxide arrester for VFTs", *IET Sci. Meas. & Technol*., vol. 11, no. 4, pp. 438-444, 2017. doi: 10.1049/iet-smt.2016.0514.

P. Valsalal is a Professor in Department of Electrical and Electrical Engineering, College of Engineering, Anna University, Chennai, India. Her area of research is surge arrester, electrical transients in power systems and EHV power transmission.