VOL. 5, NO. 11, NOVEMBER 2010 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

EXPERIMENTAL STUDIES FOR SURGE VOLTAGE RESPONSE OF A POWER TRANSFORMER MODEL WINDING PROVIDED WITH METAL OXIDE VARISTORS

Mohd. Zahed Ahmed Ansari[1], G. R. Gurumurthy[2] and J. Amarnath[3]
[1]Department of Electrical and Electronics Engineering, Ghousia College of Engineering, Ramanagaram, Karnataka, India
[2]Department of Electrical and Electronics Engineering, BNM Institute of Technology, Bangalore, Karnataka, India
[3]Department of Electrical and Electronics Engineering, JNT University, Hyderabad, Andhra Pradesh, India
E-Mail: zahedansari@gmail.com

ABSTRACT

Surge voltage distribution across a power transformer winding due to appearance of very fast rise transient overvoltages (VFTO) such as lightning surges consists of high voltage oscillations and the voltage distribution along the length of the winding can be highly non-uniform. In order to make the voltage distribution more uniform along the length of winding under these conditions, a method has been explored as an alternate to the conventional methods that are being used presently. This method consists of providing suitably designed metal oxide varistors (metal oxide surge absorbers) across sections of winding. The voltage - current characteristic of metal oxide varistor (MOV) is given by $V = KI^{\beta}$, where K and β are the constants of MOV. Experimental investigations have been carried out on a transformer model winding with MOVs provided across fifty percent and hundred percent of winding length to investigate surge voltage performance of these types of windings for appearance of lightning overvoltage (full impulse voltages) at line terminal of the model winding. Transformer windings with α values 5.6, 11.8 and 18.9 have been analyzed. The oscillographic records obtained with presence of identical MOVs (MOVs having similar characteristic constants K and β) or non-identical MOVs (MOVs having different K value and similar β) across transformer winding sections show appreciable reduction in surge voltages across sections of winding as compared to that obtained without MOVs.

Keywords: surge voltage distribution, lightning overvoltage, metal oxide varistors, transformer model winding.

1. INTRODUCTION

Transformers are one of the most important equipments used in power transmission systems. Transformers in service are exposed to hazards due to effects of lightning phenomena [1-4]. Lightning overvoltages having very fast rise times of value 1µs or lower can cause considerable hazard to transformer winding insulation because of non-uniform voltage distribution along the length of the winding. Therefore it is of great importance to make the voltage distribution along the length of transformer winding to be as uniform as practicable. In earlier years this was achieved by use of static end rings provided at line terminal of HV winding of transformer. Other methods that were employed for making the voltage distribution more uniform is by increasing series capacitance of the winding (C_s) by suitably interleaving the winding or by decreasing winding capacitance to ground (C_g) using shielding to the transformer winding. Few recent investigations have shown that, because of excellent surge protection performance capabilities, a suitably designed MOV can be used across sections of power transformer HV winding to improve the voltage distribution along the length of winding [5-6]. The voltage distribution along the length of HV winding of transformer is mainly dependent on α value (Square root of the ratio of total ground capacitance to total series capacitance of the winding) of the winding.

In previous investigations [6], simulation analysis for surge voltage behavior of power transformer winding was studied for appearance of unit step voltages at HV terminal of model winding by performing computer simulations.

Experimental studies have been carried out on a transformer model winding to investigate surge voltage response due to appearance of lightning impulse voltage at line terminal. The voltage - current characteristic of MOV is highly non-linear and is given by $V = KI^{\beta}$, where K and β are the constants of MOV. MOVs of similar characteristic constants K and β and also of different K values and similar β value have been used across the sections of winding for these investigations. The results of the investigations are reported in this paper. The values of α used in this work are 5.6, 11.8 and 18.9.

2. TRANSFORMER MODEL WINDING FOR SURGE STUDIES

The HV winding has been represented by a single layer coil wound on an insulating former of mean diameter 20.1cms and coil consisting of 8 sections. Each coil section constituted 60 turns. Thus, the HV winding equivalent circuit of power transformer winding for investigating surge voltage behavior of winding which consist of several similar sections, each of the sections represented by self inductance (L) and mutual inductance between sections (M_{12},…M_{21}….M_{48}……M_{84}..etc.), series capacitance across winding sections (C_s) and capacitance between coil section to ground (C_g) is shown in Figure-1 [1-3]. Suitable MOVs are also connected across each section of the winding.

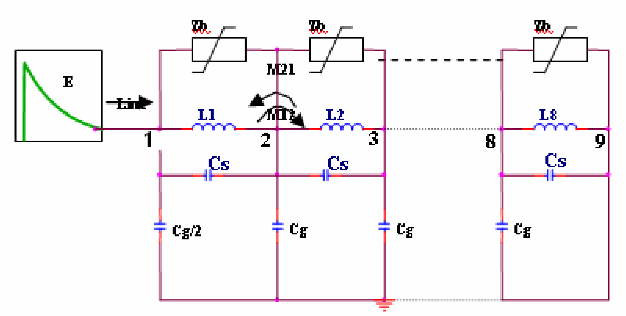


Figure-1. Equivalent circuit representation of transformer HV winding including mutual inductances for impulse voltages with MOVs across all sections.

3. EXPERIMENTAL DETERMINATION OF CHARACTERISTIC CONSTANTS K AND β OF MOV

The circuit shown in Figure-2 has been used for determination of constants of MOV (surge absorber blocks), K and β. The capacitor bank C_b was charged to a known voltage and voltage at points p and q with respect to ground were recorded using the Digital storage oscilloscope (Agilent make DSO 5034A, 300MHz, 2GaS/s, 4-Channel). Different varistors of voltage ratings of 40, 50, 60, and 95 volts were selected for purposes of experimental investigations. These low voltage varistors have been selected from consideration which require that the maximum voltage across the model winding should not be higher than 2000V and it is desirable that the maximum value of input voltage at line terminal is much below this maximum voltage. Also, the varistors should be functioning in the nonlinear region ($V = KI^{\beta}$) so that the surge voltage distribution along length of the winding is improved.

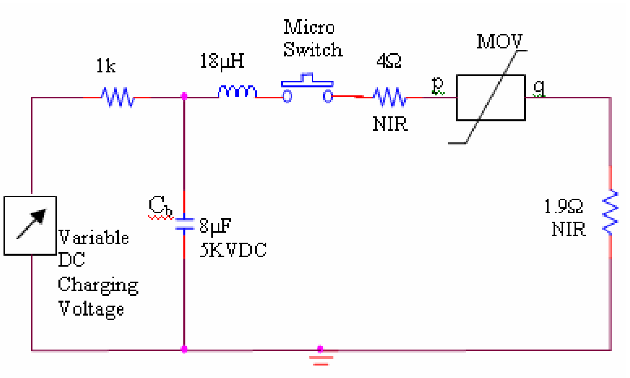
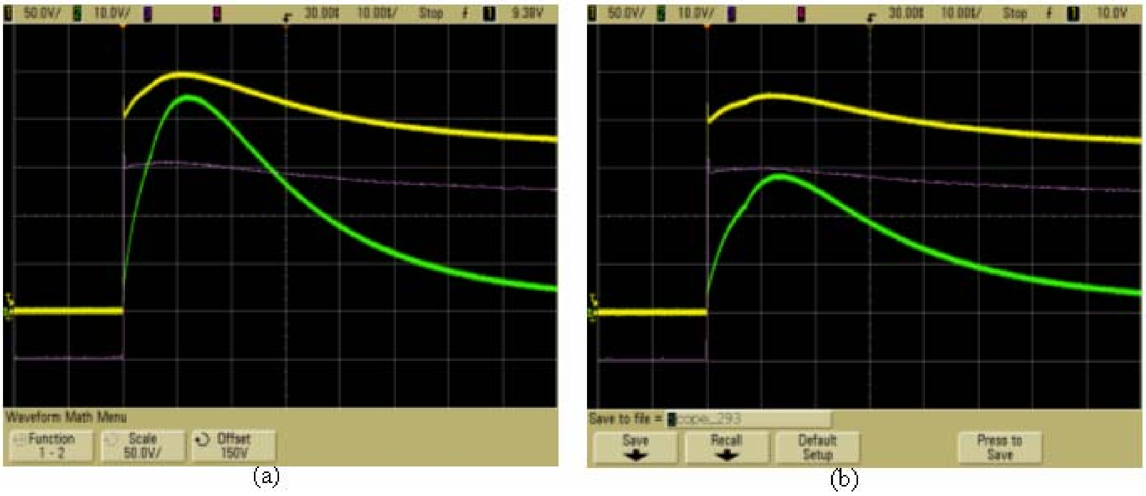


Figure-2. Circuit diagram for measurement of MOV constants.

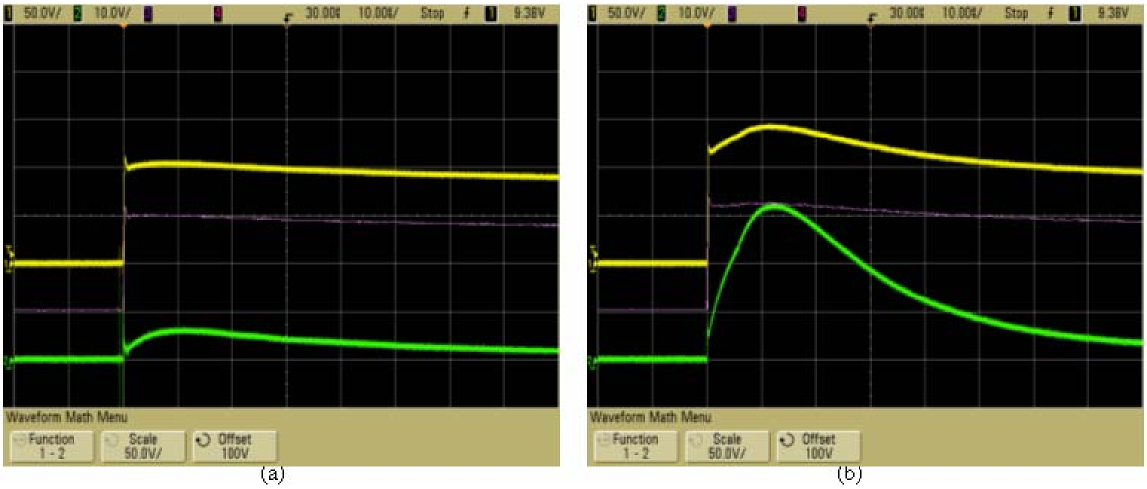
Depending upon the voltage rating of the varistor, two values of charging voltages for capacitor bank C_b were selected. The capacitor bank was charged to any of these voltages and voltage to ground at point p and q were recorded (Figure-2). Few of these recorded oscillogaphs are shown in Figures 3 and 4.

Sufficient numbers of samples were tested so that values of β in the range 0.04 to 0.06 could be used for the experimental investigations on the model winding. Some of the representative experimental results obtained are shown in Table-A1 of Appendix 1.



(a) (b)

Figure-3. Varistor voltages at point's p, q and ground, respectively for MOV rating of 95v.



(a) (b)

Figure-4. Varistor voltages at point's p, q and ground, respectively for MOV rating of 40v. (V_{pg} – Yellow, V_{qg} – Green, V_{MOV} – Purple).

4. EXPERIMENTAL SETUP

A surge generator consisting of a capacitor bank of total capacitance 0.2µF along with a spark gap and waveshaping components were built for purposes of carrying out experimental investigations on the model winding. The best waveshape that could be obtained across the line terminal and ground of the transformer model winding was a front time of 1.4 µs (± 30% tolerance) and a tail time of 50µs (±20% tolerance). Several alterations of above circuit were tried including connection of a low value capacitance (of order of 1000pf) at line terminal to ground. These introduced peak oscillations of magnitude ±15% (approximately). The circuit used for achieving this waveshape after several trials with the components is shown in Figure-5 along with transformer model winding.

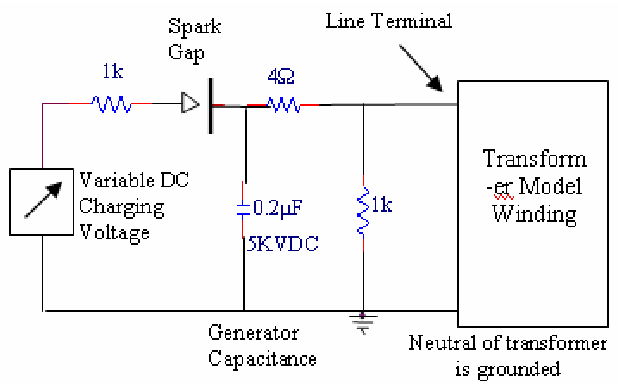


Figure-5. Schematic diagram for surge voltage measurement with MOVs connected across sections of transformer model winding (Figure-2).

A photograph of the experimental setup used for investigations of surge voltage distribution with MOVs provided across sections of winding is shown in Figure-6. The apparatus used in this setup are listed below:

a) Transformer model winding
b) MOV connected across the winding section
c) Low voltage impulse generator
d) Digital storage oscilloscope
e) Auto transformer (0-270V)
f) Step up transformer (220V - 7.5kV)

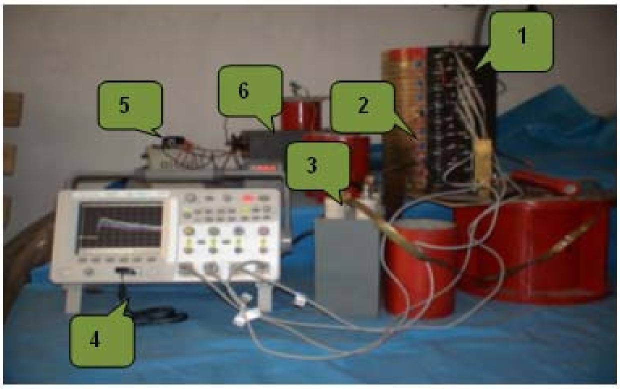


Figure-6. Experimental setup used for investigations of surge voltage response with MOV.

5. RESULTS AND DISCUSSIONS

5.1 Surge voltage response of transformer model winding for lightning impulse voltage without MOV

The surge generator output is connected to the line terminal of the model winding (Figure-5). The winding under experimental investigation is neutral grounded type. The ground terminal of model winding is connected to surge generator ground.

The voltages at different terminals along the length of model winding with respect to time for values of α equal to 5.6, 11.8 and 18.9 for a standard lightning impulse voltage of front time 1.4µs (±30% tolerance) and tail time of 50µs (±20% tolerance) applied at the line terminal of equivalent circuit of transformer model winding without MOV are recorded. The representative oscillographic record of the surge voltages at different nodes to ground with respect to time and without MOVs are shown in Figures 7 to 9 for the α value 11.8.

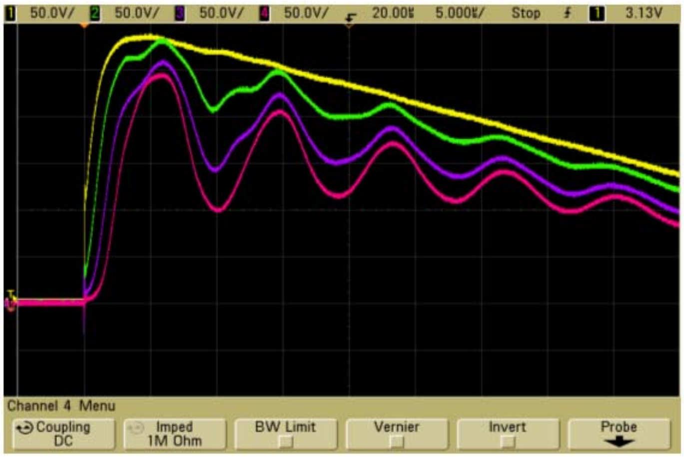


Figure-7. Per unit surge voltages at different nodes to ground 1, 2, 3 and 4 with respect to time without MOV (α = 11.8)

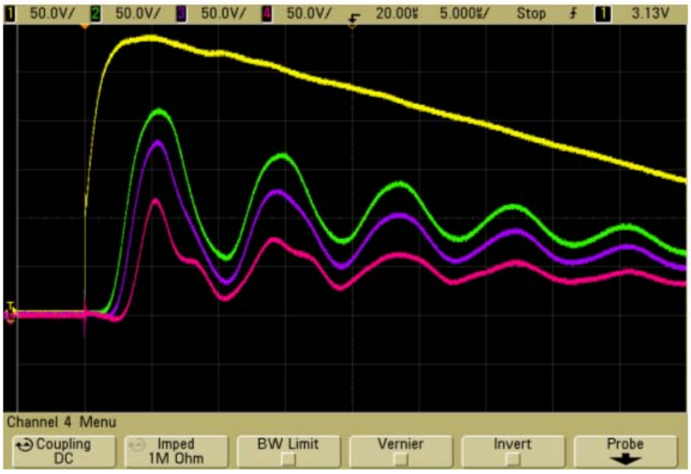


Figure-8. Per unit surge voltages at different nodes to ground 1, 5, 6 and 7 with respect to time without MOV (α = 11.8).

Figure-9. Per unit surge voltages at different nodes to ground 1, 7, 8 and 9 with respect to time without MOV (α = 11.8).

5.2 Surge voltage response of transformer model winding for lightning impulse voltage with MOV across 50% of winding length

When MOVs of similar characteristic constants K and β (K = 105 and average value of β = 0.055) are connected across 50% of winding length, the surge voltage response for an impulse voltage input at line terminal gives oscillation only at those nodes of the winding where MOVs are not connected. The oscillographic record obtained in this case are shown in the Figures 10 to 12 for α = 11.8.

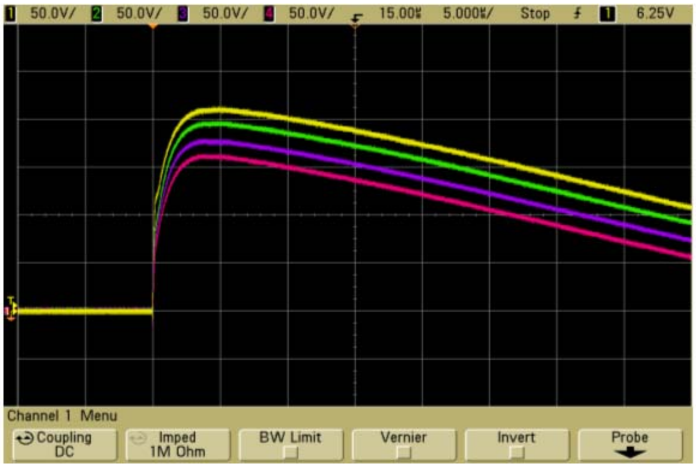


Figure-10. Per unit surge voltages with MOV provided across 50% of the winding length at nodes 1, 2, 3 and 4 to ground with respect to time (α = 11.8).

Figure-11. Per unit surge voltages with MOV provided across 50% of the winding length at nodes 1, 5, 6 and 7 to ground with respect to time (α = 11.8).

Figure-12. Per unit surge voltages with MOV provided across 50% of the winding length at nodes 1, 6, 7 and 8 to ground with respect to time (α = 11.8).

The maximum stresses in this case occur across section between nodes 5-7 and 8-9 and these are respectively 27% and 31.76%. However, the voltages across sections provided with MOVs are considerably less and the maximum value is less than 12%.

5.3 Surge voltage response of transformer model winding for lightning impulse voltage with MOV across 100% of winding length

The surge voltage distribution across sections of winding when all the sections are provided with MOVs of similar characteristics constants K and β (Average K = 105 and average β = 0.055) for α values 5.6, 11.8 and 18.9 were recorded. The representative oscillographic recordings for α value 11.8 are shown in Figures 13 to 15. We observe from these figures that there are no oscillations on waveform of voltage to ground at different node positions of the winding. The maximum value of surge voltages across any section of the winding in this case has reduced to 19.4%, 16.6% and 17.1% for α values 5.6, 11.8 and 18.9, respectively.

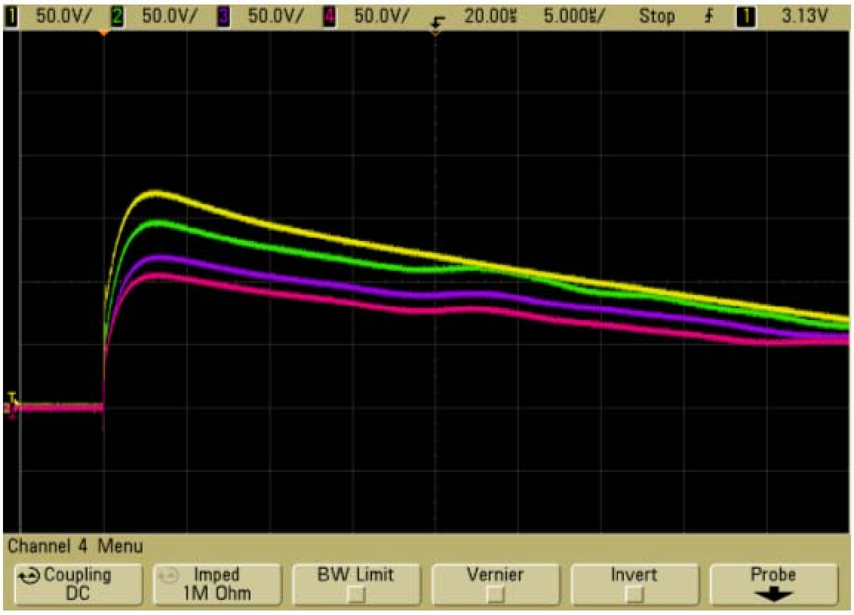


Figure-13. Per unit surge voltages with MOV provided across 100% of winding length at nodes 1, 2, 3 and 4 to ground with respect to time (α = 11.8).

Figure-14. Per unit surge voltages with MOV provided across 100% of winding length at nodes 1, 5, 6 and 7 to ground with respect to time (α = 11.8).

Figure-15. Per unit surge voltages with MOV provided across 100% of winding length at nodes 1, 6, 7 and 8 to ground with respect to time (α = 11.8).

A comparative analysis of the magnitude of maximum voltages appearing across sections of the model winding without and with MOVs of similar characteristics connected across all the sections of winding are plotted in Figures 16 to 18 for the three α values.

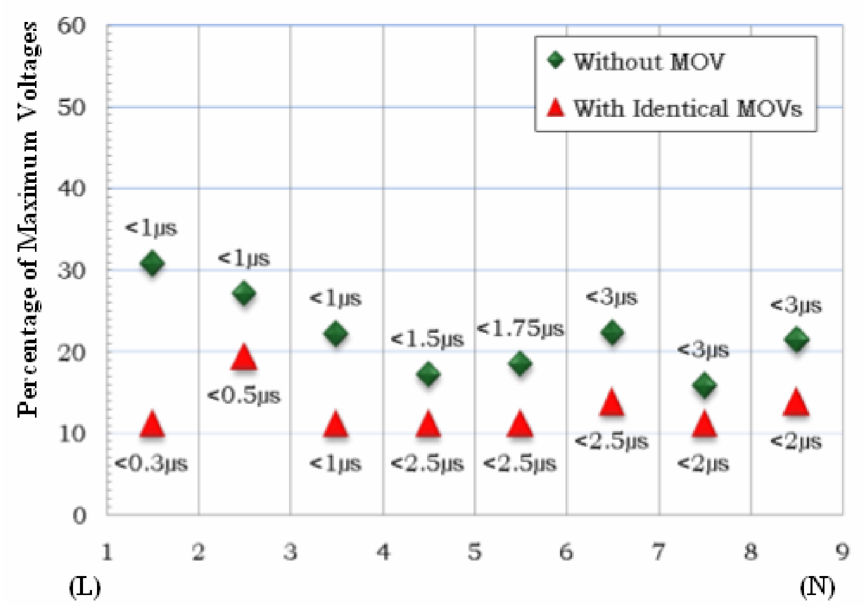


Figure-16. Maximum voltages across sections of winding without and with identical MOVs indicated between the corresponding nodes of the transformer model winding (α = 5.6) (L) = Line end. (N) = Neutral end. *Time Instant at which maximum voltage appear between the nodes.

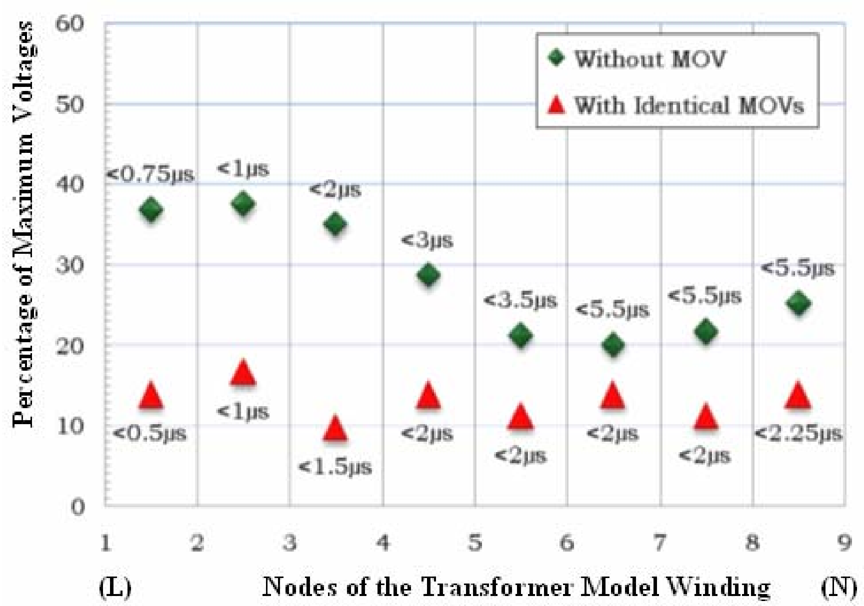


Figure-17. Maximum voltages across sections of winding without and with identical MOVs indicated between the corresponding nodes of the transformer model winding (α = 11.8).

In these Figures, the maximum voltage appearing across section between terminals of winding is indicated at the middle point between terminals along with the time instant of occurrence of maximum voltage stresses.

Similar experimental investigations were performed by connecting MOVs of different K values like 175.9, 175.9, 130.6, 130.6, 103.3, 103.3, 95.6 and 95.6 across sections 1-2, … 7-8 respectively. The average value of β used is 0.055. The representative oscillographic recordings for α value 18.9 are shown in Figures 19 to 21.

We observe from these figures that there are no oscillations on waveform of voltage to ground at different node positions of the winding. The maximum value of surge voltages across any section of the winding in this case has reduced to 19.3%, 19.3% and 15.8% for α values 5.6, 11.8 and 18.9, respectively.

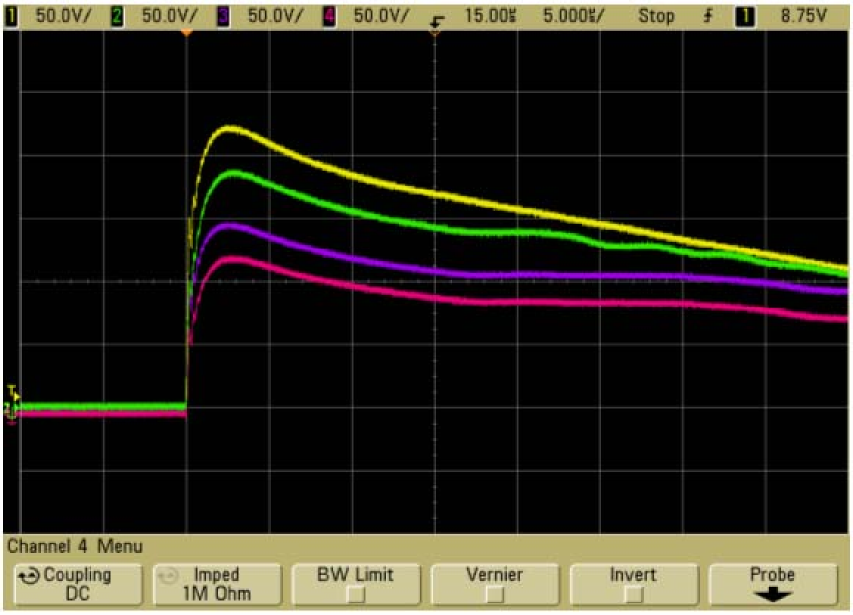


Figure-19. Per unit surge voltages with Non-Identical MOV provided across 100% of the winding length at different nodes 1, 2, 3 and 4 to ground with respect to time (α = 18.9).

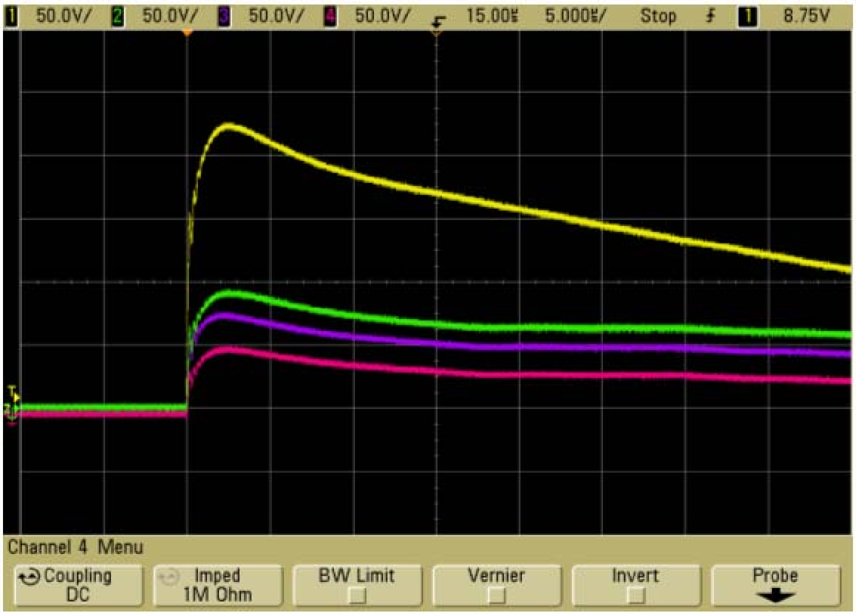


Figure-20. Per unit surge voltages with Non-Identical MOV provided across 100% of the winding length at different nodes 1, 5, 6 and 7 to ground with respect to time (α = 18.9).

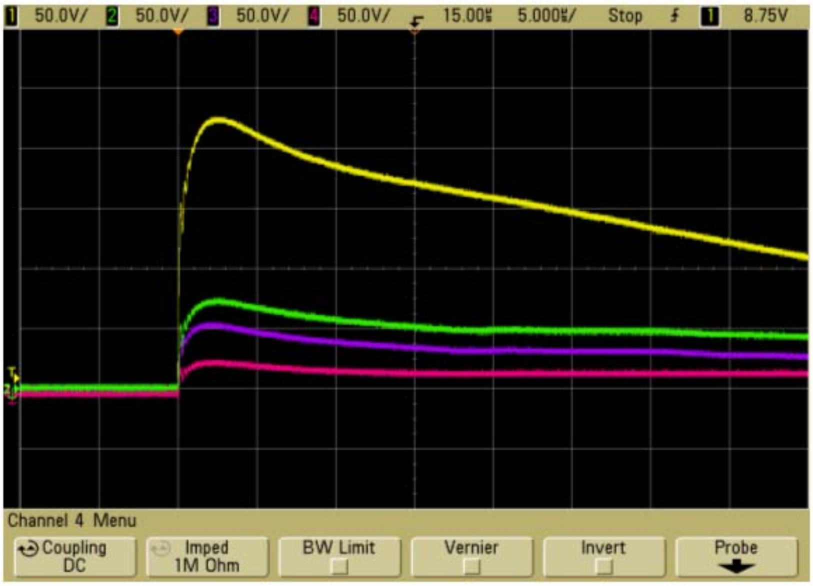


Figure-21. Per unit surge voltages with Non-Identical MOV provided across 100% of the winding length at different nodes 1, 6, 7 and 8 to ground with respect to time (α = 18.9).

A comparison of voltage stresses across transformer model winding sections without and with MOVs of dissimilar characteristic constants (Different K and Similar β) for α values 5.6, 11.8 and 18.9 are respectively shown in Figures 22 to 24 for lightning impulse voltage.

It can be observed from Figures 16 to 18 and Figures 22 to 24 that voltage stresses across sections of transformer winding have been considerably reduced by providing MOV blocks across all the sections of transformer model winding irrespective of whether identical or non- identical MOVs are connected across the sections of winding. However, for non-identical MOVs provided across sections some of the sections can be affected with increased voltage stress as compared to that obtained with identical MOVs.

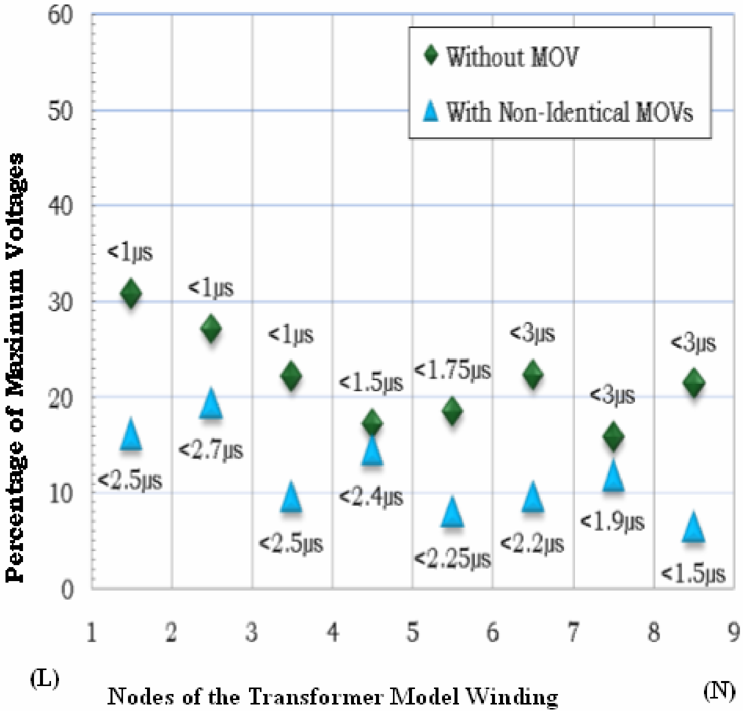


Figure-22. Maximum voltages across sections of winding without and with non-identical MOVs indicated between the corresponding nodes of the transformer model winding (α = 5.6).

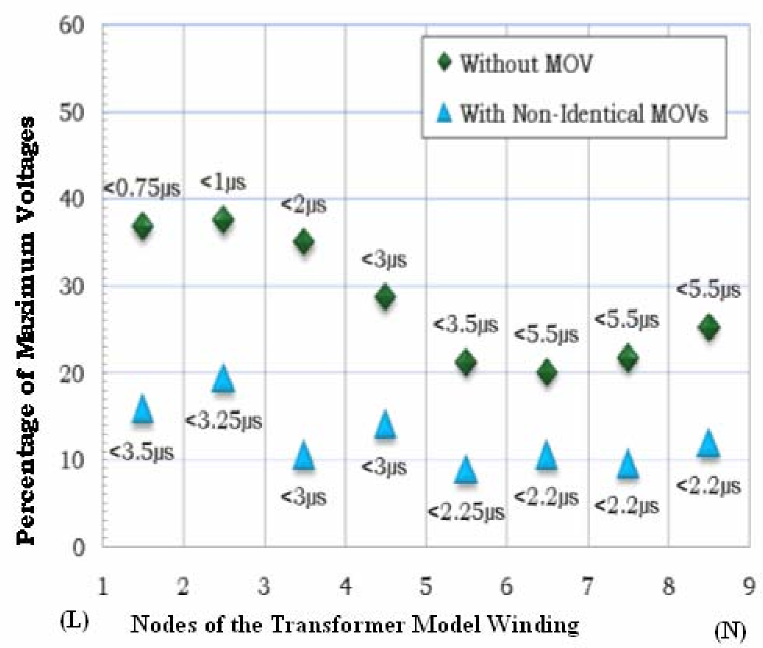


Figure-23. Maximum voltages across sections of winding without and with Non-Identical MOVs indicated between the corresponding nodes of the transformer model winding (α = 11.8).

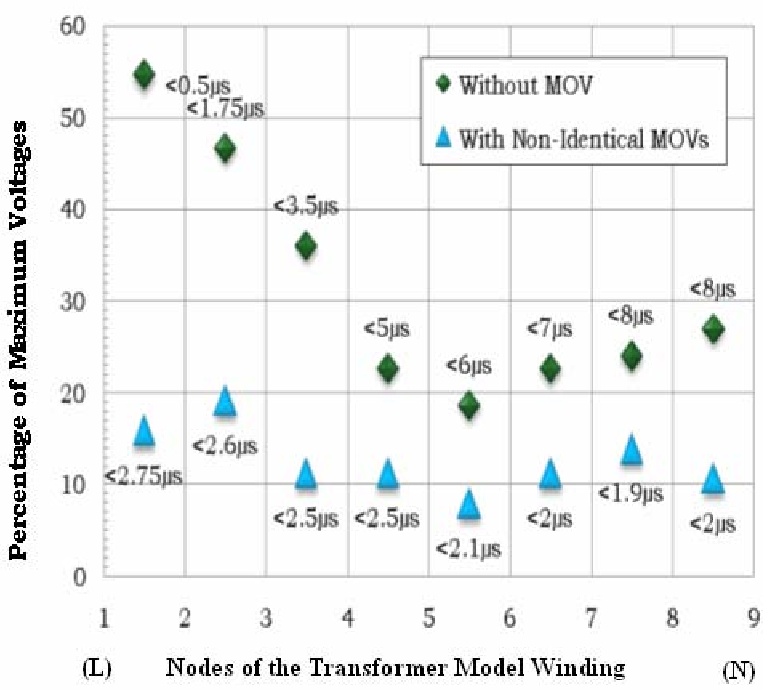


Figure-24. maximum voltages across sections of winding without and with non-identical MOVs indicated between the corresponding nodes of the transformer model winding (α = 18.9).

6. CONCLUSIONS

The Experimental investigations carried out on a transformer model winding for α values 5.6, 11.8 and 18.9 and for appearance of lightning impulse voltage at the line terminal of model winding have given rise to the following conclusions:

a) The surge voltage response of a transformer model winding without MOVs across sections of winding consists of voltage oscillations of natural frequencies.
b) By providing MOVs of similar characteristic constants K and β across 50% of winding length, the surge voltage stresses are reduced to a considerable extent

across those sections where MOVs are provided. The oscillations in voltage waveform appear only at nodes to which MOV terminals are not connected.

c) By providing MOVs of similar characteristic constants across 100% of winding length, surge voltage stresses across the sections of winding are considerably reduced and there are no oscillations in the voltage waveform at any of the nodes.
d) In case where MOVs of dissimilar characteristic constants (i.e., different K and similar β values) are provided across all the sections of winding, there is a reduction in surge voltage stresses across sections of winding and no oscillations appear in voltage waveform.
e) By providing suitable MOVs across sections of model winding, the maximum value of voltage to ground at any of the nodes does not exceed the peak value of the input impulse voltage at line terminal.

ACKNOWLEDGMENTS

The author Mohd. Z. A. Ansari would like to thank the authorities of Ghousia College of Engineering, Ramanagaram and JNTU, Hyderabad, the author G. R Gurumurthy would like to thank authorities of BNM Institute of Technology, Bangalore, for all the cooperation and encouragement.

REFERENCES

[1] L. F. Blume, Boyajian G. Camith, T.C Lennox, S. Minneci, V.M Montsinger. 1952. Transformer Engineering. John Wiley and Sons.

[2] S. B Vasutinsky. 1962. Principles, operation and design of power transformer. PSG College of Technology, Coimbatore, Tamilnadu, India.

[3] B. Heller and A. Veverka. 1968. Surge phenomena in electrical machine. Iliffe Books Ltd, London.

[4] E. Kuffel, W. S. Zaengl and J. Kuffel. 2000. High voltage engineering fundamentals. Newnes (Butterworth- Heinemann).

[5] Wen Yuanfang and Chengke Zhou. 2005. Experimental studies on the use of MOV in transformer windings inner protection. IEEE Trans. on power delivery. 20(2): 1441-1446.

[6] Yuanfang Wen and Chengke Zhou. 2004. A novel method for predicting the life time of MOV. IEEE Trans. Power Delivery. 19(4): 1688-1691.

[7] Mohd. Z. A. Ansari, G. R. Gurumurthy, J. Amarnath and N. K. Kishore. 2006. Surge Voltage Stresses Across Power Transformer Winding Sections Provided With Metal Oxide Surge Absorber Blocks. Proceedings of IEEE International Conference on Electrical Insulation and Dielectric Phenomena (CEIDP-2006). 16th -19th October. Held at Kansas City, Missouri, USA. pp. 229-232.

Appendix 1

Table-A1. Experimental data for determination of K and β of MOV.

#	**Varistor rating** (volts)	**Capacitor bank charging voltage** (volts)	**Measured values** (volts)		V_{MOV} (V_p-V_q)	**Current through MOV** (amps)		**β**	**K**
			V_p	V_q		I_1	I_2		
1	95	200	185	7	178	1.4	-	0.05	175.9
		250	225	32	193	-	6.4		
2	60	150	142.5	9	133.5	1.8	-	0.04	130.6
		190	175.0	34	141	-	6.8		
3	50	120	112.5	7	105.5	1.4	-	0.06	103.3
		160	142.5	27	115.5	-	5.4		
4	40	100	100	4.7	95.3	0.94	-	0.05	95.6
		140	130	26	104	-	5.2		