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# Complexities in Design and Manufacturing of Transformers with Low MVA, High Voltage Class

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## SUMMARY

Power Transformers are the most critical and complex products in the transmission network system. These products are specified through various stringent technical norms from the electrical utilities and are governed in line with international or national standards. The most important part is framing the technical norms to define these product capacities in terms of Mega Volt Amperes (MVA) and voltage (kV) class. Inappropriate framing of transformer specifications i.e. transformers with higher MVA and lower voltage class or lower MVA with higher voltage class reflects in higher complexities for both design and manufacturing.

This paper describes the various challenges associated with design and manufacturing of such lower MVA ($\leq$ 20 MVA) and high voltage class ($\geq$132 kV) transformers. The major challenge in di-electric design of windings for withstanding transient voltage surges has been demonstrated in this paper. The paper address the theoretical principles and philosophies associated with distribution constant of lightning impulse. The related simulation of these impulse voltages has been performed through electrostatic tool for four different cases of transformer. For low MVA transformers ($\leq$ 20 MVA), the Impulse voltage distribution is found to be more vulnerable with relatively poor safety margins as compared to higher MVA transformers ($\geq$ 60 MVA) for windings of same voltage class.

Along with this, the paper focus on operational constraints of positioning the regulating winding in a transformer. It is very complex to accommodate regulating winding inside the main windings gaps in constant ohmic type of low MVA high voltage transformers, which is a very usual practise in transformer manufacturing for achieving certain inter winding impedances at different tap positions. The options become further limited if third stabilising winding is present in such transformers. Furthermore, the High Voltage (HV) winding lead routing is also a complex task from the perspective of dielectric clearances due to space constraints in low MVA transformers as compared to high MVA transformers.

The simulation results with strong evidence of poor impulse voltage distributions with very low safety margins in low MVA transformers as compared to high MVA transformers have been demonstrated in result section, taking reference of 132 kV winding with same test level of 650 $kV_p$.

**KEYWORDS**

Transformer; Distribution constant; Ground capacitance; Series capacitance; Impulse voltage distribution; Interleaving; Low MVA; High voltage.

## 1. INTRODUCTION

Transformers are electrical static devices used for transferring energy between two circuits based on electromagnetic induction phenomenon. They link circuits at different voltage levels and are vital links for interconnecting different components of power systems including generation, transmission and distribution networks operating at their respective voltage levels. Therefore, their application in power system govern basic parameters of transformers such as voltage rating, MVA, impedance, losses along with other parameters such as tapping range, no. of phases, vector group, noise level etc. These parameters demand in-depth analysis for designing Power Transformers. There has been a rapid increase in these parameters of Power Transformers with capacity of single unit approaching to 750MVA, having extra high voltage levels of 800kV class, which may give perspective of relatively simpler design for low MVA transformers such as 10-20 MVA. Instead, low MVA and high voltage Power Transformers are one of the complex transformers from design and manufacturing point of view.

There is no consolidated published literature that has reported the enormous challenges in design and manufacturing of low MVA and high voltage transformer. Authors have published the case study of stringent impulse voltage distribution in low MVA, high voltage transformers [1] and along with that, this paper has summarised various other complexities related to design and manufacturing of such transformers.

## 2. CHALLENGES IN LOW MVA AND HIGH VOLTAGE TRANSFORMERS

### 2.1 Impulse voltage distribution across windings

The foremost challenge in low MVA and high voltage transformers is related to winding design based on impulse voltage distribution. Transformers are subjected to lightning strikes and switching operations that lead to very high frequency overvoltage transients in the windings [2]. Therefore, capability to withstand these transient voltage surges is very critical consideration while deciding geometry and type of transformer windings.

The study of winding response to overvoltage transients is an electrostatic problem as during impulse voltage, it is only due to capacitances of winding that charge is allowed into the winding [3].The distribution constant ($\alpha$) [4] which drives the initial distribution of impulse voltage in a winding is a function of winding capacitance to ground ($C_g$) along with its series capacitance ($C_s$), and is given as:

$$\alpha = \sqrt{\frac{C_g}{C_s}} \tag{1}$$

The voltage distribution along the height of winding with grounded neutral for different values of α has been shown in Fig. (1).

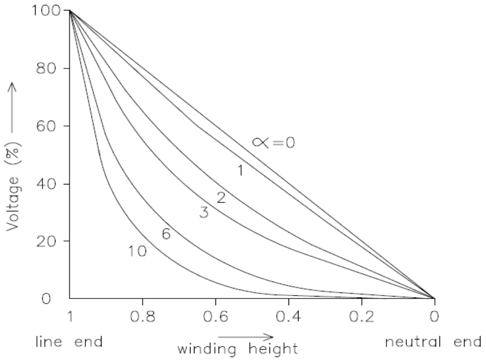

Fig. 1 Initial voltage distribution along the height of winding

It is clear from Fig. (1) that if $\alpha$ is close to zero the voltage distribution in winding is almost uniform and it would significantly increase the winding strength under lightning voltages. However, for $\alpha = 10$, the 80% of voltage is appearing in only 20% top portion of winding which would lead to huge stress concentration at line end terminal of winding .So, for attaining preferred low values of $\alpha$, in order to have improved voltage distribution in windings [5], $C_g$ should be as low as possible and $C_s$ should be as high as possible.

However, when MVA rating of transformers are low, particularly below 20 MVA, the response of Disc windings to impulse voltages become relatively poor as compared to the response of transformers above 60MVA for test levels including and above 132 kV class. This is due to low series capacitance of windings, $C_s$, which lead to high values of $\alpha$. The necessary formulation for capacitances, $C_s$ and $C_g$, along with reasoning behind poor response of low MVA transformers has been given in detail as under.

The $C_g$, include inter winding capacitances, $C_{gw}$, and capacitance between winding and tank/core, $C_{gt}$ [6]. The inter winding capacitances, $C_{gw}$, can be calculated as:

$$C_{gw} = \frac{\varepsilon_{\circ} \Pi\, D\, H}{\frac{t_{oil}}{\varepsilon_{oil}} + \frac{t_{solid}}{\varepsilon_{solid}}} \tag{2}$$

where, in Eq. (2) $D$ denotes the mean diameter of inter winding gap, $H$ is the winding height, $t_{oil}$ and $t_{solid}$ denotes the oil and solid insulation thickness in inter winding gaps, and, $\varepsilon_{oil}$ and $\varepsilon_{solid}$ denotes relative permittivity of oil and solid insulation.

Capacitance between outer winding and tank can be calculated as:

$$C_{gt} = \frac{2\Pi \varepsilon_{\circ} H}{cosh^{-1}(\frac{d_{wt}}{R})} \left[\frac{t_{oil} + t_{solid}}{\frac{t_{oil}}{\varepsilon_{oil}} + \frac{t_{solid}}{\varepsilon_{solid}}}\right] \tag{3}$$

where, in Eq. (3) $R$ denotes the radius of winding and $d_{wt}$ is the distance between the winding axis and tank.

So, from Eq. (2) and Eq. (3) it is clear that there is very limited scope in varying $C_g$ of winding, which is a function of $C_{gw}$ and $C_{gt}$, as most of its parameters, such as inter-winding gaps or circumference of winding are more or less fixed as per considerations of electrical design. However, sometimes it is done by discs shielding from ground, but it is not a preferred option due to space constraints, as it will add extra cost to total cost of transformer.

Therefore, the major impact on improving impulse voltage distribution in windings can be attributed to improving $C_s$.

The total series capacitance of winding, $C_s$ is consisted by inter turn capacitances ($C_t$) and capacitance between discs ($C_d$) which are given by Eq. (4) and Eq. (5) respectively as under:

$$C_t = \frac{\varepsilon_{\circ}\varepsilon_p * \Pi\, D\, (w + t_p)}{t_p} \tag{4}$$

where, in Eq. (4) $D$ denotes winding mean diameter, $w$ denotes bare conductor width, $t_p$ is thickness of paper insulation on both sides and $\varepsilon_p$ relative permittivity of paper insulation.

$$C_d = \varepsilon_{\circ} \left[\frac{k}{\frac{t_p}{\varepsilon_p} + \frac{t_s}{\varepsilon_{oil}}} + \frac{1-k}{\frac{t_p}{\varepsilon_p} + \frac{t_s}{\varepsilon_s}}\right] * \Pi\, D(L + t_s) \tag{5}$$

where, in Eq. (5) $L$ denotes radial depth of winding, $t_s$ denotes thickness of spacers between discs, $\varepsilon_s$ denotes solid insulation relative permittivity and k is the fraction of oil area with respect to total circumferential area.

So, it is clear from Eq. (4) and (5) that most of the parameters of inter-turn and inter-disc capacitances are dependent on geometrical considerations and these are in series in complete winding.

From $C_t$ and $C_d$, the total capacitance, $C_s$ of Disc winding can be calculated as:

$$\mathrm{C}_s = \frac{C_t}{N_{disc}\, N_t^{\;2}}\,(N_t - 1) + \frac{4\,(N_{disc} - 1)}{3\,N_{disc}^{\;2}}\,C_d \qquad (6)$$

where, in Eq. (6) $N_{disc}$ denotes number of disc and $N_t$ denotes number of turns per disc. So, it can be established that $\mathrm{C_s}$ is inversely proportional to number of turns per disc and number of discs.

Therefore, the major difference in $C_s$ is due to number of turns in a winding. For series capacitive network, if more capacitances are in series then the net value of total capacitance is less. Similarly, in a disc winding for a particular value of inter-turn capacitance ($C_t$), and capacitance between discs ($C_d$), if number of turns ($N_t$) and discs ($N_{disc}$) are more, the net series capacitance of a winding will be less. Same philosophy can be applied to layer winding that if number of turns are more, then equivalent $\mathrm{C_s}$ will be less [7].

On comparative basis, $C_s$ is less due to more number of turns in low MVA transformers. So, more number of turns means more capacitances in series, which eventually leads to lower $C_s$ and higher value of α.

The reason behind more number of turns in low MVA transformers can be understood from basic equation:

$$\frac{V}{T} = 4.44\ \mathrm{f\ B\ A} \qquad (7)$$

where, B is flux density and f is frequency. As per Eq. (7) Voltage per turn, $\frac{V}{T}$, is directly proportional to cross-sectional area of core, A, and in low MVA transformers core area are quite less and thus, giving low values of V/T, as compared to high MVA Transformers where core area are relatively high. Hence, winding of a particular voltage class in a low MVA transformer will have more number of turns and discs than that of a high MVA transformer. Thus, $C_s$ value is less for same voltage class of winding in low MVA transformer. In other words, disc winding in low MVA transformer has more concentration of stress at line end terminal during impulse voltage.

Hence, it is necessary to improve $C_s$ of disc winding in low MVA transformers by inter-shielding or inter-leaving methods, while in high MVA transformer disc winding construction of same voltage class can withstand same levels of impulse voltage.

The series capacitance, $C_s$, of interleaving winding can be calculated as:

$$\mathrm{C}_s = \frac{C_t}{4}\,[(N_t) + (\frac{N_t - 1}{N_t})^2 (N_t - 1) \qquad (8)$$

It is clear from Eq. (8), that interleaving winding give substantial increase in $C_s$ with more turns per disc, $N_t$, since in that case two physical adjacent turns will be more electrically apart. So, the disadvantage of more turns per disc in disc winding for low MVA transformers, converts into an advantage for interleaving winding from point of view $\mathrm{C_s}$. However, manufacturing of interleaving windings is not only complex but also a time consuming process.

The results validating less safety margins for disc winding in low MVA transformers have been published using example of 10 MVA and 20 MVA 220/132/33 kV Transformers. The results have been compared with relatively high MVA transformers i.e. 60 MVA and 100 MVA where safety margins of disc winding are more, which imply that same winding types are able to withstand same impulse voltage levels, when MVA rating of a transformer is high. The results of 10MVA and 20MVA transformers with interleaving winding has also been discussed in Section 3.

## 2.2 Regulating Winding Design

Another challenge in low MVA transformers is to design regulating winding, which is used to meet the voltage variation as specified by adding or subtracting the number of turns in steps to main winding through a tap changer device. Its design is complex from perspective of manufacturing in certain cases of low MVA, high voltage transformers.

It has already been explained that as per Eq. (7), the value of $\frac{V}{T}$, is less for low MVA transformers, as compared to high MVA transformers. Therefore, the number of turns required to achieve the step voltage are very high in low MVA transformers. So, even most commonly used tapping ranges will have quite high number of turns in regulating winding for low MVA transformers. For example, in the four cases considered in this paper, with high voltage variation of ± 10% in steps of 1.25% of 220 kV i.e. 2.75 kV, the comparative turns per step of 2.75 kV are given in Table I:

Table I. Comparison of number of turns per step of 2.75kV

| Transformer Rating | Turns/step |
|---|---|
| 10 MVA 220/132/33 kV | 3.5 x N |
| 20 MVA 220/132/33 kV | 2.5 x N |
| 60 MVA 220/132/33 kV | 1.4 x N |
| 100 MVA 220/132/33 kV | N |

So, the 10 MVA transformer is having 3.5 times number of turns than the 100 MVA transformer for achieving same step voltage of 2.75 kV. This limits the available options for designing regulating winding.

From manufacturing point of view, regulating winding is preferred as outermost winding because leads for each step need to be routed to tap changer device and it becomes more feasible if tap winding is outermost winding as shown in Fig. 2a. However, in case to have highest impedance value at minimum voltage tap like in constant ohmic transformer type, the regulating winding is placed inside the high voltage winding. This can be conveniently done in high MVA transformers due to less number of turns, but corresponding to more number of turns in low MVA transformers, it becomes very complex to accommodate this winding inside the other windings. When regulating winding is inside the other windings, it can only be manufactured as layer winding because leads for each step can only be taken axially out at top or bottom of regulating winding due to presence of other winding over it as shown in Fig. 2b.

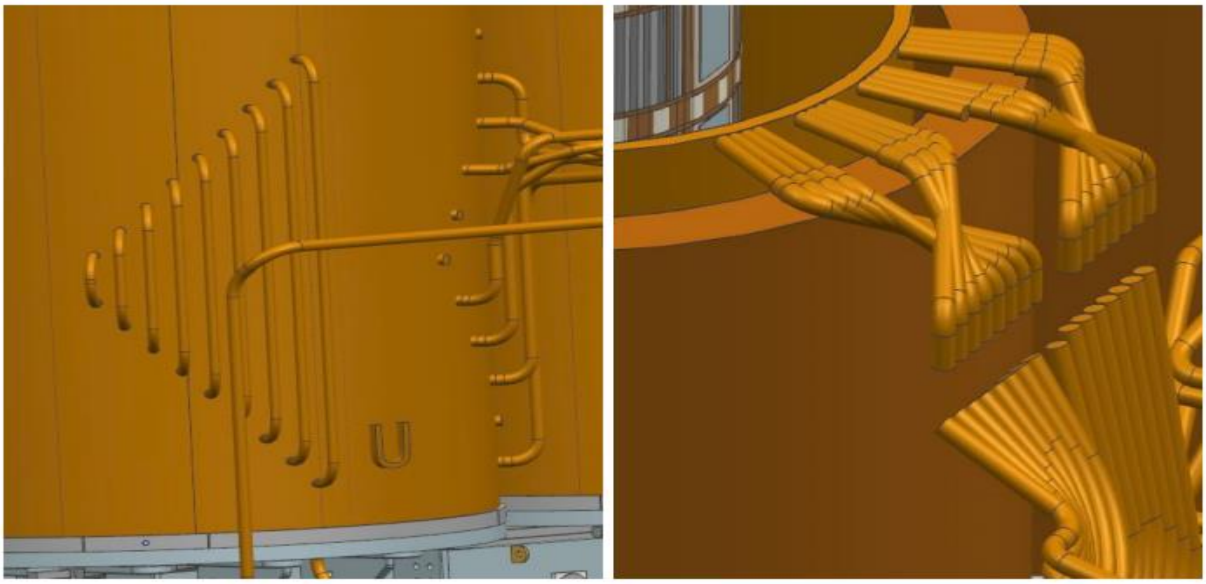

Fig.2 a) Outermost regulating winding b) Inner regulating winding

So, accommodating high number of turns in layer winding under geometrical constraints of winding height is a complex task. Sometimes multi- layer winding construction need to be adopted which would certainly increase the complexity of winding construction due to accommodation of more turns in multiple layer geometry and moreover, handling huge number of leads from multi-layer regulating winding becomes very complicated for manufacturers.

### 2.3 Stabilising Winding Design

An additional delta connected stabilising winding can be used in wye-wye connected transformer for stabilizing neutral voltage, reduction of third harmonics, controlling zero sequence impedance or sometimes to serve load. Even if third winding is used for stabilising purpose only and can have no outside terminals, but still it has to be designed for stability in case of asymmetrical faults in other High Voltage and Low Voltage windings, being single line to ground (SLG) fault as most severe. Hence, stabilising winding conductor size should be so chosen that it can withstand mechanical stresses during these fault conditions.

However, the other way to improve withstand capability of stabilising winding is by increasing inter-winding impedances which can be easily done by adopting certain reliable techniques related to winding position. However, positioning of this winding in the defined compact magnetic geometry is a great challenge in low MVA transformers. In simple words, with already so many considerations, the design of stabilising winding sometimes make situations more complex with very limited choices available related to its position with respect to other main windings.

### 2.4 Routing of High Voltage Leads

After winding manufacturing, the winding leads are routed to the bushings by maintaining clearances as per their voltage levels, which is again a rigorous task in low MVA, high voltage transformers. The operationally proven lead routing for high voltage winding is by taking two parallel parts as shown in Fig. 3a, as it becomes more feasible to maintain sufficient clearances from other earth parts such as frame with line end lead of highest voltage winding at centre.

However, in case of low MVA transformers due to very low amperes it is not advisable to have two parallel parts, but high voltage winding with one single part having line end lead at top of winding adds extra complexity to route the lead. In such transformers, if high voltage winding is positioned in the main gap and not as outermost winding then lead can be either taken out radially, but in that case sufficient clearances need to be maintained not only from top earth parts such as frame, but also from top of outside other windings. In some cases the lead is taken axially out with and angular displacement as shown in Fig. 3b which is a big risk as angular bending creates additional mechanical stress in lead insulation.

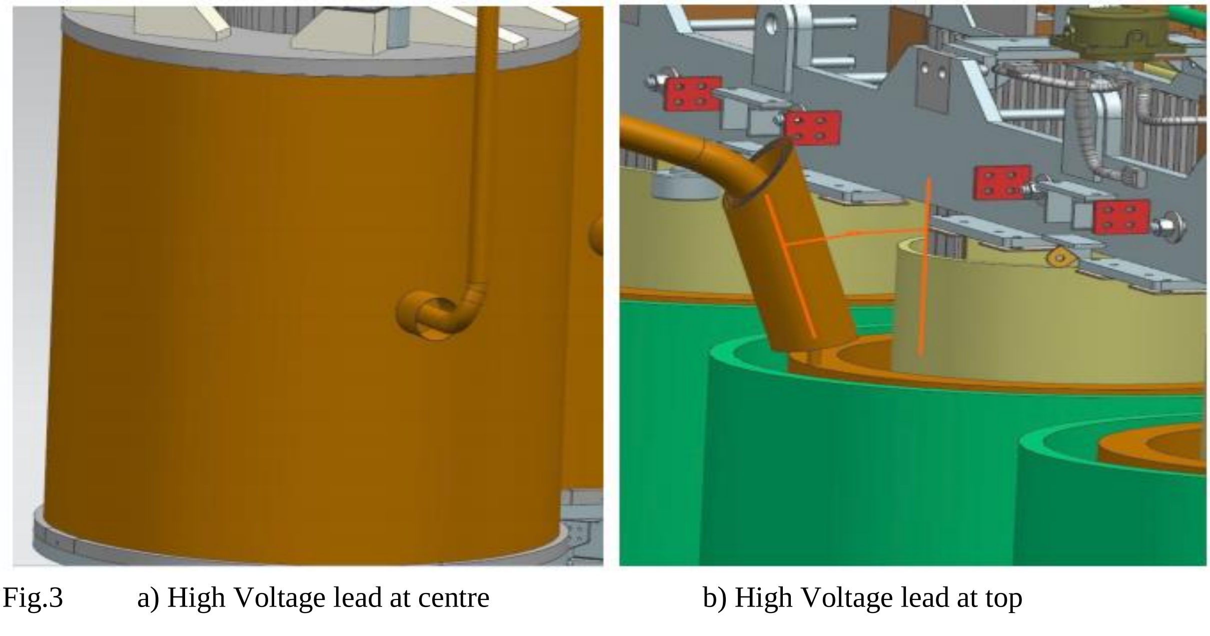

Fig.3 a) High Voltage lead at centre b) High Voltage lead at top

Conclusively, in low MVA transformers for same voltage levels, the design and manufacturing becomes more complicated with only limited options available regarding winding positions and lead routing.

Regarding challenge of impulse voltage distribution, the response of same type of winding with same voltage test levels of impulse in four different MVA ratings of transformer has been discussed in detail as under.

## 3. RESULTS AND DISCUSSION

The results are based on simulation of impulse voltage distribution in four different cases of transformers as under:

Case 1 : 10MVA 220/132/33kV
Case 2 : 20MVA 220/132/33kV
Case 3 : 60MVA 220/132/33kV
Case 4 : 100MVA 220/132/33kV

All the four ratings of transformer are with similar winding disposition. The results have been compared taking reference of distribution of 650 kVp impulse voltage in 132 kV winding in all the four ratings. The safety margin between discs, which can be calculated by Eq. (9), has been plotted for discs at line end terminal of winding.

$$\text{Safety Margin} = \frac{\text{Withstand voltage level}}{\text{Actual appeared voltage}} \qquad (9)$$

Here, the actual voltage is based on distribution constant α, while withstand level is based on dielectric design of winding. The results have been discussed as under:

**Case 1 and 2 : 10 MVA and 20 MVA 220/132/33 kV Transformer with disc type winding**

Safety margin between discs at line terminal of 10 and 20 MVA, 220/132/33 kV transformer are given in Fig.4.

Here, the safety margins of 10 MVA transformer are found to be less than 1.0 in few discs at line end terminal of 132 kV winding with disc type construction and it means that the actual voltage appearing between discs is more that the withstand level of disc-disc insulation. Comparatively, the safety margins in 20 MVA transformer are found to be better than 10 MVA transformer for same voltage class winding with similar disc type winding construction, because for same voltage class winding the 20 MVA transformer will have lesser turns and eventually better Cs and lower α than 10 MVA transformer.

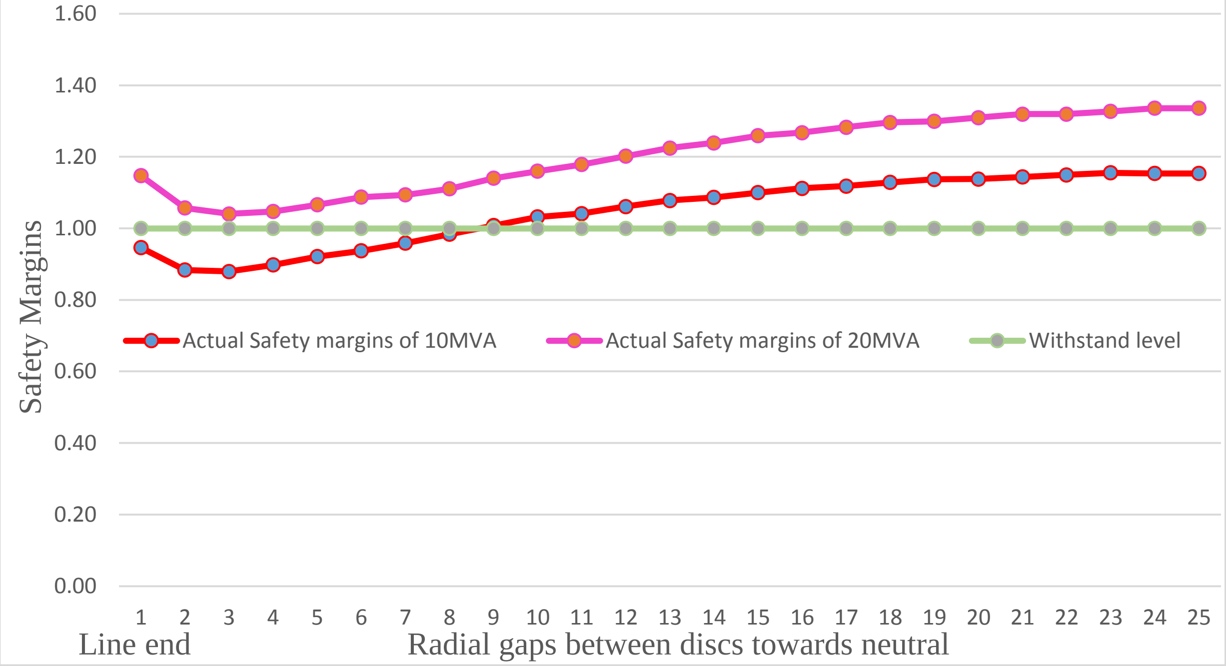

Fig. 4 Safety margins of 132 kV disc winding in of 10 MVA and 20 MVA transformer

However, even in 20MVA transformer the safety margins are very close to 1.0 in discs at line end terminal of winding, with minimum value of 1.04 and it is always advisable to have additional safety of 10%. Therefore, in both the transformers because of more voltage stress concentration at line end of winding, the $C_s$ of winding need to be improved in order to have more uniform voltage distribution across winding.

**Case 3 and 4 : 60 MVA and 100MVA 220/132/33 kV Transformer with disc type winding**

The impulse voltage simulation results and corresponding safety margin of discs in 60 and 100 MVA, 220/132/33 kV transformer are given in Fig. 5.

Here, disc winding construction for 132 kV winding is able to withstand impulse voltage of 650 kVp, as the safety margins are found to be more than 1.0 for both 60 and 100MVA transformers, with minimum value of 1.12 in 60 MVA and 1.89 in 100 MVA. Therefore, normal disc type 132 kV winding, which is relatively simple from perspective of manufacturing, can be used in transformers.

Comparatively, 100MVA transformer is having least turns as compared to other three transformers and therefore, it will have highest $C_s$ and lowest value of α as compared to 10, 20 and 60 MVA transformer of same voltage rating. The total voltage is most uniformly distributed throughout the 132 kV winding in 100MVA transformer for same test level of 650 kVp.

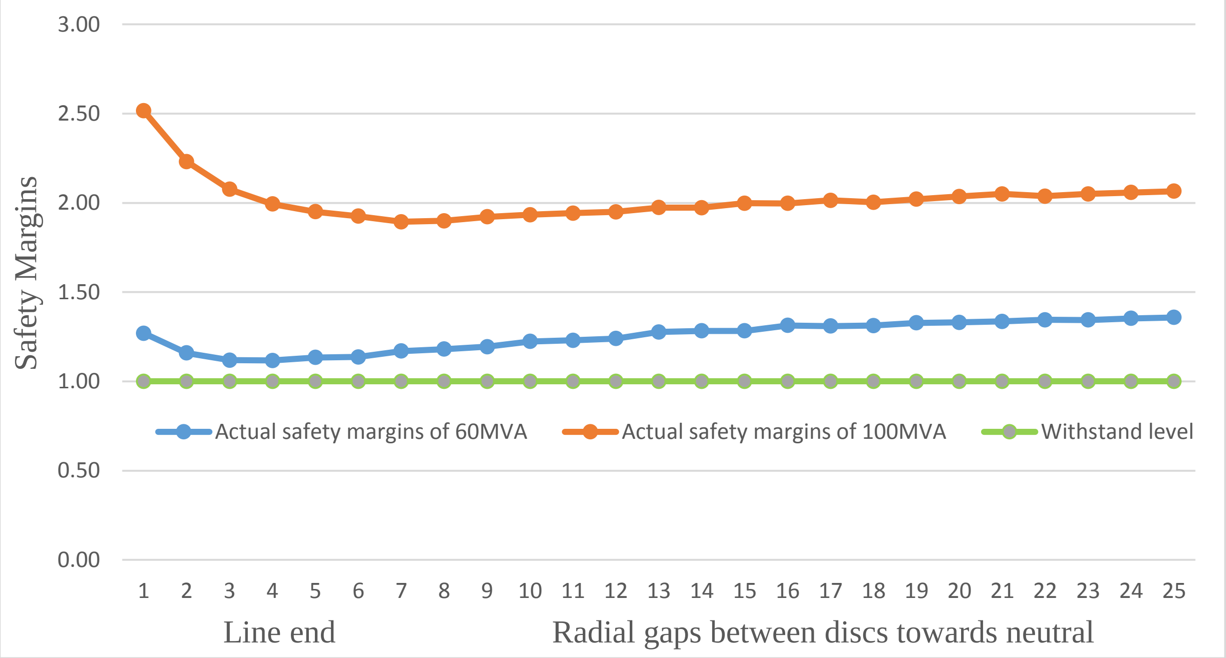

Fig. 5 Safety margins of 132kV disc winding in of 60 MVA and 100 MVA transformer

**Case 1 and 2 : 10 MVA and 20 MVA 220/132/33 kV Transformer with Interleaving type winding**

Interleaving is the most proven and preferred solution to improve series capacitance of winding. As, $C_s$ need to be improved in 10 MVA and 20 MVA transformer, so with interleaving type winding the motive of keeping two physically adjacent turns more electrically apart can be better achieved in low MVA, high voltage transformers pertaining to more turns.

The results of simulation with 132 kV voltage class interleaved winding in 10 MVA and 20 MVA 220/132/33kV transformers are given in Fig. 6.

With interleaving winding the safety margins have significantly improved in both 10 and 20MVA transformers. Comparatively, the safety margins in 10 MVA transformer are found to be better than 20 MVA transformer with interleaving type construction.

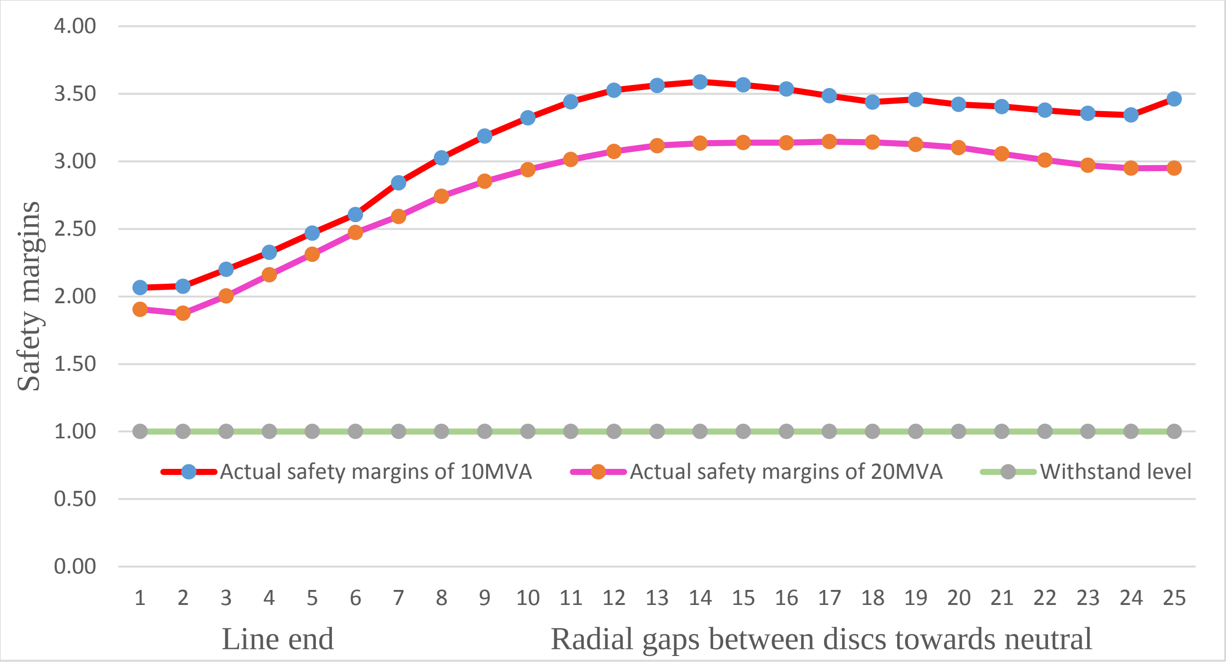

Fig. 6 Safety margins of 132kV interleaved winding in 10MVA and 20MVA transformer

The winding with more number of turns will be more vulnerable with disc winding construction as observed in 10MVA transformer which has minimum safety margins for 132kV disc winding, but in interleaving winding more turns in disc is an advantage, as two physical turns will be more electrically apart and therefore, 10MVA transformer with interleaved type 132kV winding has maximum safety margins for same test level of 650 kVp.

## 4. CONCLUSION

The paper elaborated the different response of same voltage class disc winding to impulse voltage based on different MVA rating of transformers. It has been clearly demonstrated that high voltage disc windings in low MVA transformers are more stressed at line end terminal as compared to high MVA transformers. The simulation for impulse voltage of 650 kVp in 132kV winding has been done for 10 MVA and 20 MVA 220/132/33 kV transformer, where safety margins are found to be very low as compared to 60 MVA and 100 MVA transformer when simulated for same test level. The benefits of interleaved winding in such low MVA and high voltage class transformers has been demonstrated along with simulation results with interleaved winding. The results of interleaved winding with significantly improved safety margins in 10MVA and 20MVA transformer has been discussed. However, interleaving type winding is more complex to manufacture.

In addition to this, the paper addressed the other challenges related to positioning of regulating and stabilising winding for achieving certain inter-winding impedances in low MVA transformers because of more turns in winding as compared to high MVA transformer for same voltage class. The challenge of high voltage lead routing in low MVA transformer has also been explained.

Finally, this paper concludes the importance of specifications for transformer rating and, therefore, MVA ratings must be in correspondence with voltage class, as transformers less than 20 MVA for 132 kV class are very complex from design and manufacturing perspective. The utilities should not relate cost of transformer to MVA rating, as these are one of the complicated and costly products to manufacture. The specification framing committees, transformer standard up gradation working groups need to consider these stringent phenomenon in low MVA transformers and formulate the transformer ratings accordingly which will result in more stable and reliable products along with minimizing complexities in manufacturing.

# BIBLIOGRAPHY

[1] H. S. Sekhon, P. Rathore and V. Dommeti, "Case Study on Effect of Transformer Rating on Impulse Voltage Distribution in Windings," 2021 IEEE 9th International Conference on Smart Energy Grid Engineering (SEGE), 2021, pp. 124-128, doi: 10.1109/SEGE52446.2021.9535007.

[2] Tomislav Župan, Bojan Trkulja, Željko Štih, Power transformer winding model for lightning impulse testing, Procedia Engineering, Volume 202, 2017, Pages 297-304.

[3] S. Pramanik and L. Satish, "Estimation of Series Capacitance for a Three-Phase Transformer Winding From Its Measured Frequency Response," in IEEE Transactions on Power Delivery, vol. 28, no. 4, pp. 2437-2444, Oct. 2013, doi: 10.1109/TPWRD.2013.2260772.

[4] M. Bagheri, B. T. Phung and M. S. Naderi, "Impulse voltage distribution and frequency response of intershield windings," in IEEE Electrical Insulation Magazine, vol. 32, no. 5, pp. 32-40, September-October 2016, doi: 10.1109/MEI.2016.7552374.

[5] R. van Nuys, "Interleaved High-Voltage Transformer Windings," in IEEE Transactions on Power Apparatus and Systems, vol. PAS-97, no. 5, pp. 1946-1954, Sept. 1978, doi: 10.1109/TPAS.1978.354691.

[6] M. S. V. Kulkarni, S. A. Khaparde, Transformer Engineering, Design, Technology and Diagnostics, Second Edition, CRC Press Taylor and Francis Group, 2013

[7] M. Bagheri, A. Hekmati, R. Heidarzadeh and M. Salay Naderi, "Impulse voltage distribution in intershield disk winding VS interleaved and continuous disk winding in power transformer," 2008 IEEE 2nd International Power and Energy Conference, 2008, pp. 387-392, doi: 10.1109/PECON.2008.4762505.