Influence of Voltage Sourced Converter Waveforms on the Dielectric Strength of Transformer Insulation

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Abstract – **Transformers connected to new HVDC system using VSC technology are exposed to continuous converter AC voltage waveforms which are typically a rectangular wave shape with a high repetitive frequency. The most commonly encountered is a two-level VSC waveform. Steep voltage steps like these results in high stresses of the insulation due to non-uniform voltage distribution across the windings. Such stresses represent a new class of stress on transformer insulation, which has been less investigated and understood.**

In this study, the influence of two-level VSC waveforms on the voltage distribution across different windings and winding sections on a large power transformer of industrial design has been analytically studied. The importance aspect of the analytical simulation was that the entire dielectric structure of the transformer (iron core, windings, insulating barriers, spacers, shields, etc) was simulated as one-entity using a custom-made program. Consequently the results can be considered to be representative of similar type of transformers operating in this environment.

The practical implications of these results on the dielectric stress of transformer insulation is discussed in relation with those stresses generated under power-frequency and standard lightning impulse voltage excitations on which are transformer designs are generally based.

Keywords – **HVDC, Two-level VSC, Transformer, Voltage distribution, Gap stress, IGBT**

I. INTRODUCTION

New HVDC transmission systems are increasingly based on voltage sourced converter (VSC) technology that uses power electronic devices with turn off capability like Insulated Gate Bipolar Transistors (IGBT) and Gate Turn-Off Thyristors (GTO). This new innovative technology provides substantial technical and economical advantages for different applications compared to conventional HVDC transmission systems based on thyristor technology.

The purpose of this section is to give a brief overview of the HVDC transmission scheme using voltage sourced converter (VSC), the type of waveforms this system generates and that seen by the transformer input terminals which are connected to this system. Figure 1 shows the main circuit diagram of a typical HVDC transmission scheme [1]. The transmission system consists of two stations, station A and station B, connected by a dc cable or an overhead line. The major components are: high voltage dc circuit; voltage sourced Converters and Transformers

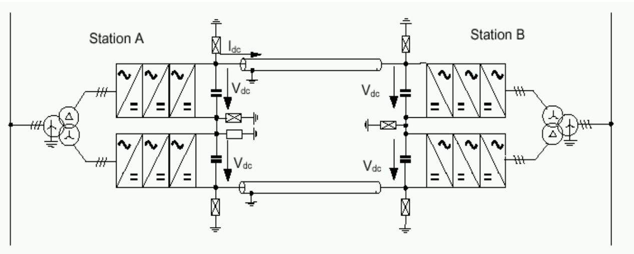


Fig. 1 Typical circuit diagram of a bipolar HVDC Transmission System

The system shown in Fig. 1 is of bipolar type. One station comprises two equally designed VSCs, each providing a DC voltage Vdc. Fig. 2 shows an example circuit diagram of a VSC. It consists of a 6 pulse bridge equipped with IGBTs (Insulated Gate Bipolar Transistors) and a anti-parallel connected 6 pulse bridge equipped with free wheeling diodes.

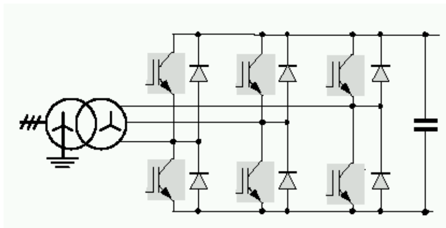


Fig. 2: Equivalent circuit of a 6 pulse IGBTs based 2 Level VSC

Figure 3 illustrates the typical output voltage waveform. It is seen that it is made up from a number of pulses that have a varying width but approximately constant magnitude; the dv/dt are expected to be rather high due to fast switching of IGBT devices.

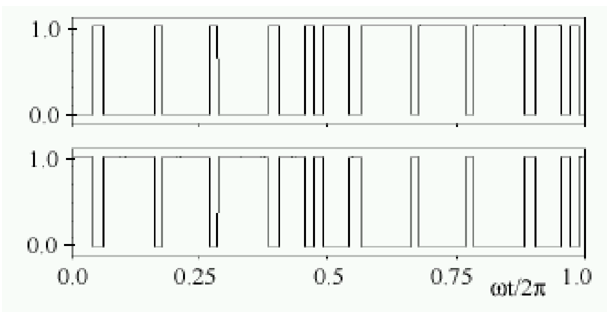


Fig. 3 Typical voltage output waveform of a two-level VSC system

An arrangement similar to that of Fig. 2 was analytically simulated using EMTDC simulation and two-level VSC waveform was generated. In an earlier study, authors studied the influence of these waveforms on a typical medium power transformer. Highlights of these investigations were that under two-level voltage excitation, the voltage distribution across high voltage winding was highly non-linear (see Fig. 4). Voltage swings under two-level excitation is bipolar, reflecting the bipolar nature of the waveform.

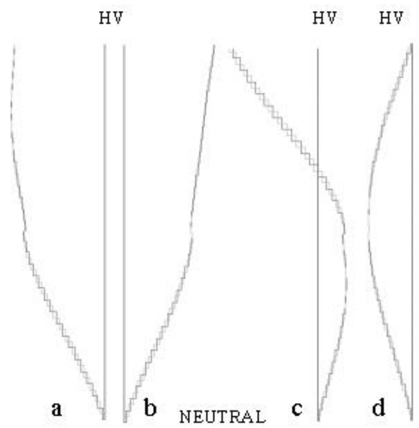


Fig 4 Voltage distribution of HV winding under two level voltage waveform excitation at different time instants.
a) At start; b) 5 ms; c) near to 15 ms; d) At end, 20 ms

Consequently, the voltage seen between different winding sections of high voltage winding, inter-turn and gap between LV and HV winding were several orders higher than those observed under 50 Hz excitation. Although these values are lower than those generated under 1.2/50 impulse voltage excitation, their continuous and repetitive nature posed a severe threat to the insulation life of transformer

The startling results of this study were thought to be partly in response to the absence of adequate line shields in the transformer design considered. Consequently a large power transformer of industrial design containing both line and neutral shields was used in this study. The influence of VSC waveforms on the voltage distribution across different winding and gap sections was analyzed.

The importance aspect of this study was that the entire dielectric structure of the transformer (iron core, windings, insulating barriers, spacers, shields, etc) was simulated as one-entity. The modelling concept is based on representing each turn of the transformer as an impedance network, which is suitable for MHz range. The applicability of this technique was demonstrated earlier [2]

The practical implications of these results on the dielectric stress of transformer insulation is discussed in relation with those stresses generated under 50 Hz and standard lightning impulse voltage excitations on which are transformer designs are generally based.

II. Specifications of Transformer Investigated

The transformer investigated is a large power transformer of industrial design. The innermost winding (tertiary, BT) is a delta-connected spiral winding in two layers. This is followed by star connected medium (MT) voltage winding. in six layers. Outer winding is a star connected high voltage (HT) spiral winding in seven layers. This is followed by tap winding (2 layers) wound in interleaved helical fashion. Line and neutral shields are positioned in between high voltage and tap windings. The schematic diagram of the transformer winding is given in Fig. A.1 of Annexe 1.

Rated Output	…	140 MVA, 3- Phase
Voltage (HV/MV/LV)	…	220 kV/ 34.5 kV / 10 kV
Connection	…	Star / Star / Delta
Tapings	…	+ 12 %
Frequency	…	50 c/s
Number of Tapings	…	25
Inner 10 kV winding	…	Spiral winding in two layers
MV 34.5 kV winding	…	Spiral winding in six layers
HV 220 kV winding	…	Spiral winding in seven layers
Tap winding	…	Interleaved helical in 2 layers

The entire dielectric structure of the transformer (core, windings, spacers, barriers, and tap-changers) was modelled with the exception of leads and bushing. Cross-section of the modelled transformer winding is shown in Fig. A.2 of the annexe. Each subdivision shown represents an element that was modelled as a inductance-capacitance network. For this study each turn of the transformer winding was modelled as one element.

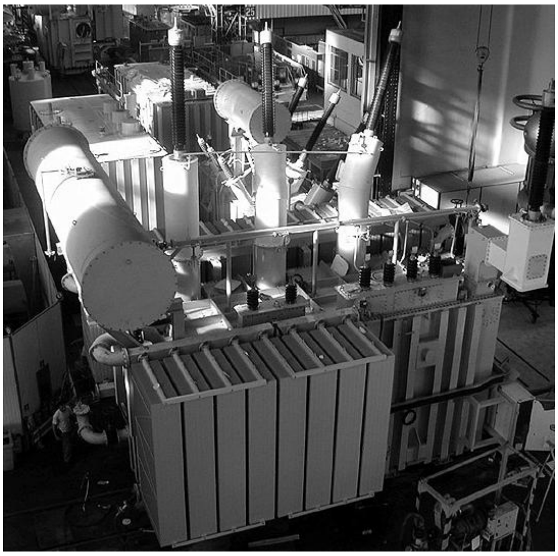


Fig. 4: Photograph of Transformer Investigated.

Fig. 5 shows an analytically generated two level VSC waveform using a circuit similar to that of Fig. 2. The switching frequency was 1950 kHz for phase-phase voltage. Exact shape of the waveform with appropriate modifications on the voltage magnitude to suit the voltage ratings of the transformers being investigation was used for analytically exciting the transformer winding for studies.

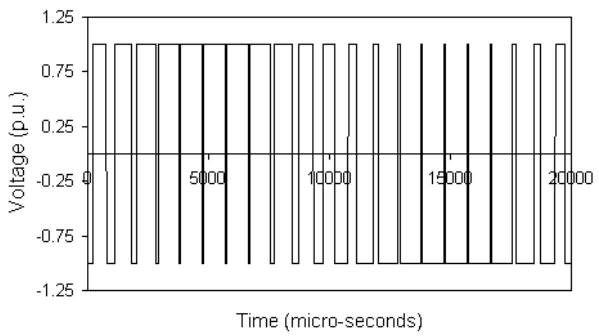


Fig. 5 Analytically generated two-level VSC waveform

III. RESULTS & DISCUSSION

In transformer design, considerable attention is given to the manner of voltage distribution across individual windings. The essential focus being to achieve an uniform voltage distribution across the axial and radial length of the winding. The transformer under investigation is of typical industrial design, designed for withstanding electrical stresses generated under conventional waveforms (like 1.2/50, 250/2500, 50 Hz waveforms). It would be thus interesting to know the behavior of the windings under the influence of two-level VSC waveforms and consequent voltages generated between different winding sections.

A Voltage Distribution across Individual Windings

To study the influence of waveshape on voltage distribution across different winding sections, highest system voltage level was used for two-level and 50 Hz waveforms and impulse BIL level for 1.2/50 standard impulse excitation. The results are reported in p.u.

Figure 6 shows the influence of two level and 50 Hz waveform on the voltage distribution across HV winding. Node number ‘1’ refers to the line end of HV winding and higher value refers to those away from line end and close to neutral end.

The shape of voltage distribution (not magnitudes) under two-level voltage waveform excitation closely follows that under 1.2/50 excitation impulse. Also, the voltage magnitude generated under two-level excitation is within 3 % margin of those generated under 50 Hz excitation. Similar observation was seen for voltage distribution across low voltage and tap windings.

However, the voltage distribution across tertiary winding under the influence of two-level, 50 Hz and 1.2/50 excitation were considerably different as revealed in Figures 7 and 8. Node number ‘1’ refers to the line end of the tertiary winding and higher value refers to those away from this.

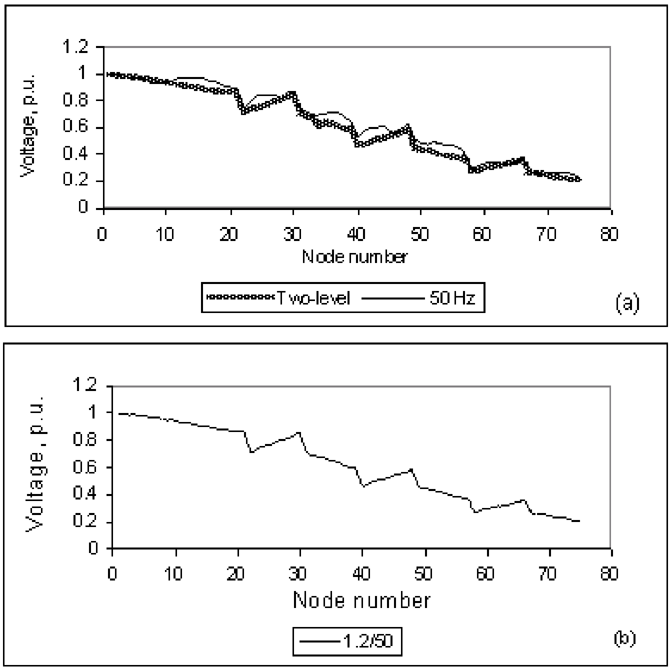


Fig. 6. Voltage distribution across HV winding under the influence of (a) two-level and 50 Hz (b) 1.2/50 impulse wave excitation.

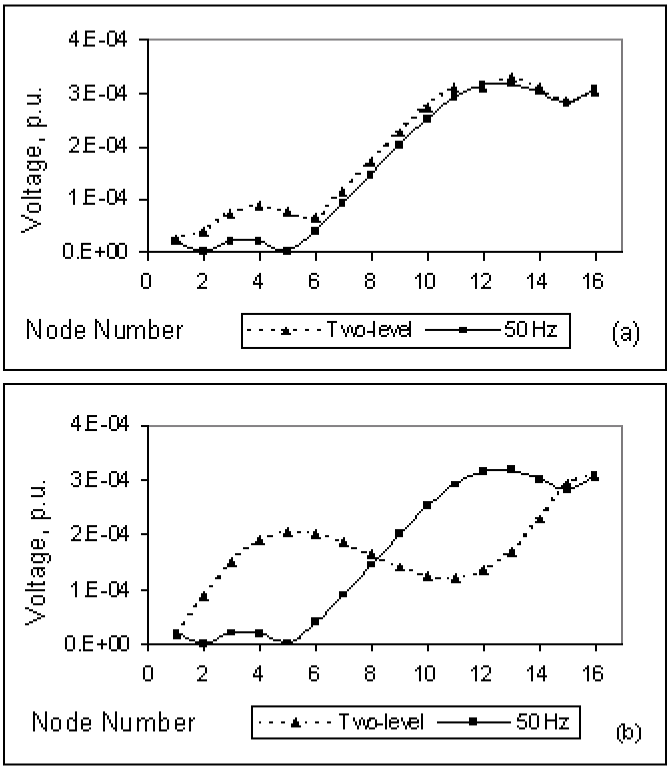


Fig. 7. Voltage distribution across Tertiary windings (TWs) under the influence of two-level and 50 Hz wave excitation. (a) TW1 (b) TW2.

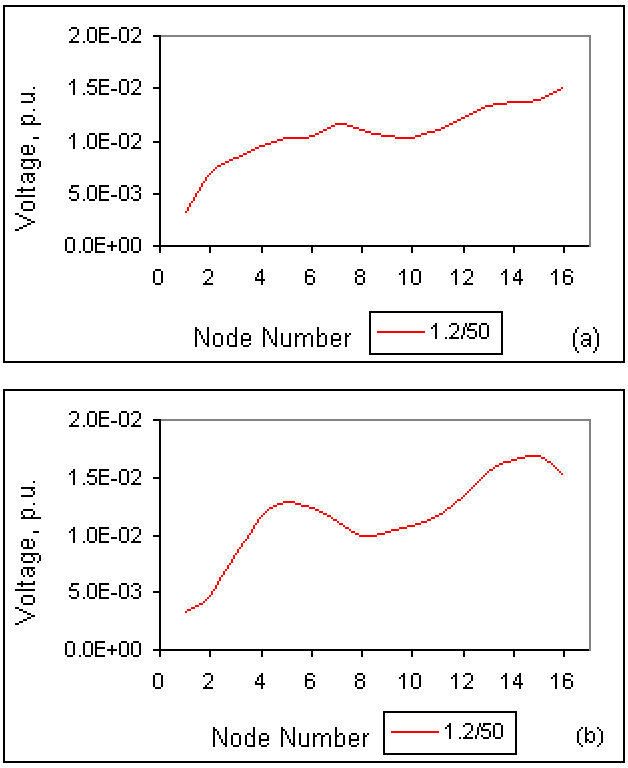


Fig. 8. Voltage distribution across Tertiary windings (TWs) under the influence of 1.2/50 impulse excitation. (a) TW1 (b) TW2.

The tertiary winding is of spiral winding type, wound in 2 layers. The shape of the voltage distribution under two-level and impulse doesn't have a close resemblance as seen across other windings of this transformer. In contrast to responses seen in other windings, the voltage distribution across tertiary winding 2 (TW2) under two-level is oscillatory with bi-directional peaks. The special nature of this voltage distribution has a detrimental influence on the gap voltage across different winding and gap sections as detailed in subsequent sections.

B. Intersection Section Winding Stress

For this study, the axial length of each layer of transformer winding (like TW1, LV1, LV2, HV1, HV2, etc) were divided into m sections. Each section comprised a group of n turns. The ranges of m and n were based upon the voltage distribution seen across the entire length of the winding. If the winding distribution was highly non-linear, then each turn of the winding was grouped as a section i.e. n =1 and m = maximum number of turns in the winding. This approach permits better estimation of voltage (stresses) across different sections and consequent knowledge of the risk posed to the winding insulation.

Figure 9 shows the differential distribution of voltage between different sections of tertiary winding. This was estimated by computing the voltage difference between two adjacent nodes. Results reveal that over-voltage is seen on first few sections of tertiary winding 1 (TW1). The over-voltage factor is about 2.5 times more than that seen under 50 Hz excitation. This is likely to influence the long-term stability of the insulation and consequently the life of the transformer.

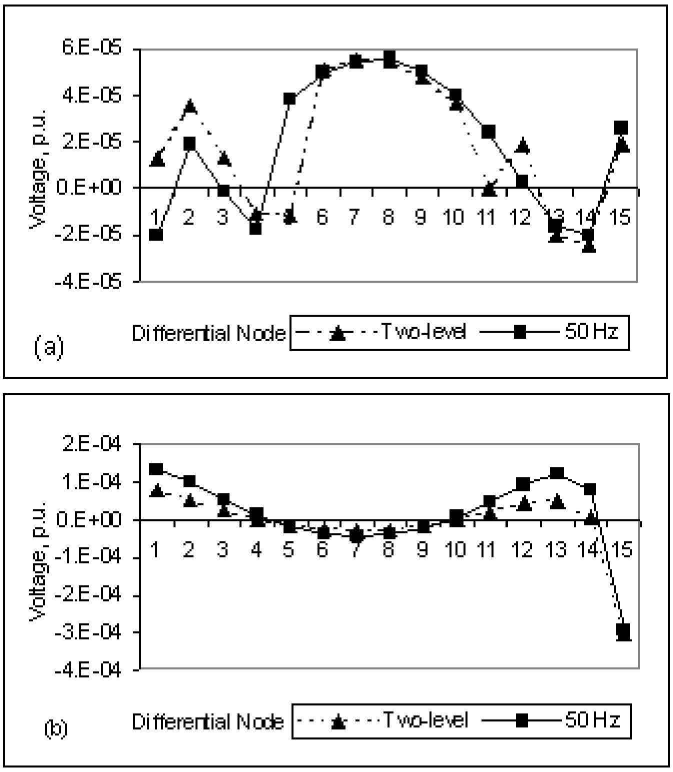


Fig. 9. Differential Voltage distribution across Tertiary windings under the influence of two-level and 50 Hz wave excitation. (a) TW1 (b) TW2.

B. Winding Gap Stress

Table 1 below compares the maximum gap voltages (stresses) at different sections of transformer winding under the influence of different waveforms. This was determined by point-by-point comparison of voltage distributed in individual nodes. Please note that values given under 1.2/50 excitation corresponds refers to BIL p.u., which in absolute voltage terms several orders higher than represented under two-level and 50 Hz.

Results reveal that gap voltage (stress) under two-level VSC waveform are generally comparable to those seen under 50 Hz, except for the gap voltage between two tertiary windings. In this case (between TW1 and TW2) , the gap voltage under two level excitation is at the least 2.5 orders more as compared to those seen under 50 Hz. This higher value is due to bi-directional voltage distribution swing seen in the tertiary winding aggravating the gap voltages.

Table 1: Comparison of gap voltage (stress) under the influence of different waveforms (the letter m against a number means that value has to be divided by 1000)

Winding Section	Two-level p.u.	50 Hz p.u.	1.2/50 BIL p.u.
Core and TW1	0.32m	0.31m	11.70m
TW1 & TW2	0.53m	0.21m	25.20m
TW2 & LV1	1.53m	1.50m	31.98m
LV1 & LV2	2.80m	2.75m	29.48m
LV2 & LV3	2.92m	2.87m	30.50m
LV3 & LV4	1.79m	1.76m	19.87m
LV4 & LV5	0.94m	0.93m	25.99m
LV5 & LV6	4.59m	4.50m	35.63m
LV6 & HV1	275.66m	0.27m	284.07m
HV1 & HV2	160.07m	159.76m	267.89m
HV2 & HV3	195.62m	194.29m	299.79m
HV3 & HV4	225.78m	224.64m	282.92m
HV4 & HV5	251.06m	250.18m	300.00m
HV5 & HV6	271.57m	270.56m	353.22m
HV6 & HV7	284.60m	282.80m	369.36m

VI. Conclusions

Investigations reveal that two-level VSC waveforms can pose a problem to the long-term serviceability of power transformer. This is especially of concern as newly evolving HVDC transmission system technology uses VSC arrangement. The highlight of this work was that for the first time the influence of VSC waveforms on the dielectric strength of large power transformer of industrial design was comprehensively studied. The added feature being the analytical simulation of the entire dielectric structure of the transformer.

The modeling concept outlined in this paper, offer a better perspective of stresses imposed on the transformer insulation under VSC waveforms and consequently a better opportunity for the transformer designer to adapt the design to this new class of stresses.

Our experience has shown that with better converter topology (3-level, etc) and appropriate selection of transformer winding technology the harmful effects of VSC waveform on the transformer insulation can be reduced considerably.

Knowledge on the long-term effect of the repetitive nature of VSC waveforms on the transformer insulation is an essential part of reliable design and this cannot be arrived out analytically and input from experimental investigations are necessary for reliable design of transformers.

References

[1] F. Schettler, H. Huang and N. Christl, "HVDC Transmission Systems using Voltage Sourced Converters – Design and Applications", Internet Literature.

[2] K. Raja, "Comparative Effects of Non Standard Waveform Excitations on Voltage Distribution of Transformer Winding" – Alstom Internal Report - FEC 01.28.

[3] K. Raja, F. Devaux and S. Lelaidier, "Comparative Effects of Surge Voltage Waveforms on the Insulation of Power Transformers fed by Voltage Sourced Converters", Annual Report 2002 Conference on Electrical Insulation and Dielectric Phenomena", pp. 105-108, 2002.

Biographies

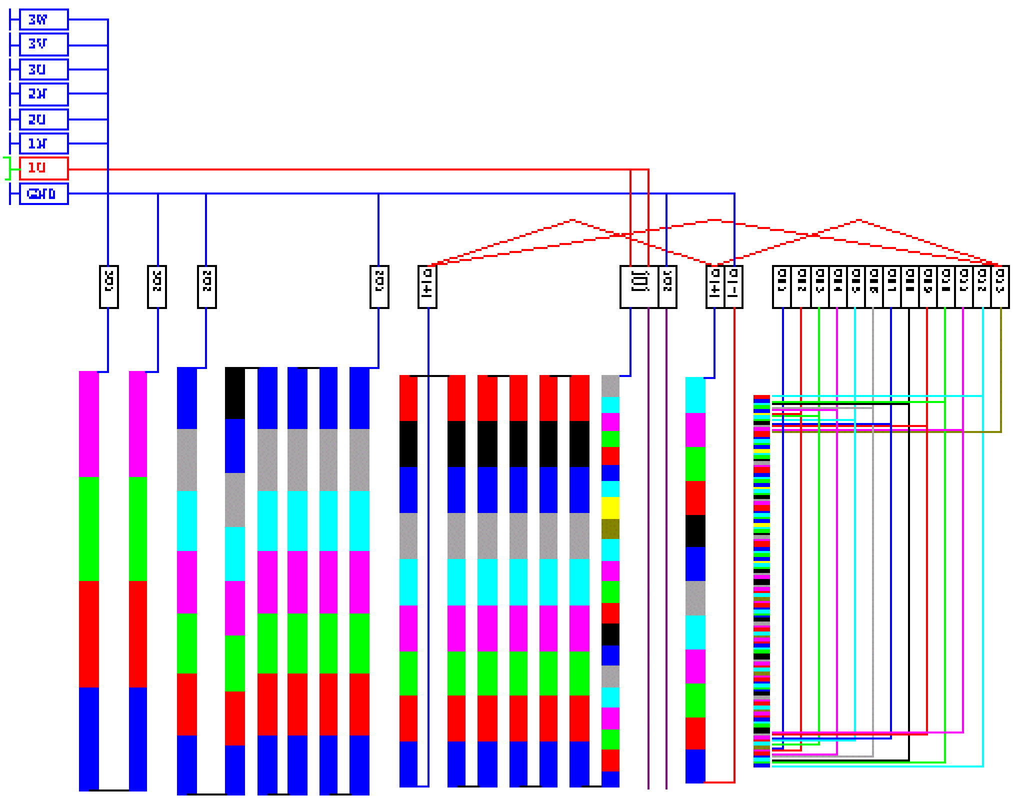
Raja KUPPUSWAMY, PhD received is Ph.D. degree in High Voltage Engineering from Indian Institute of Science, India in 1996. He has over 7 years experience in developmental studies on transformers and bushings. His experience includes development of partial discharge based high voltage instrumentation, condition monitoring software for substation equipment and transformer modelling. He is currently Research Projects Manager for Transformer Research Center, ALSTOM. He is a member of IEEE and Dielectrics and Electrical Insulation Society.

François Devaux was graduated in 1982 at French engineering school named Ecole Polytechnique and in 1984 at the French Engineering school named Ecole Supérieure des Techniques Avancées with specialisation in Industrial Engineering . He joined Alstom in 1984 as transformer development engineer . In the nineties, he was Head of Saint Ouen transformer factory Engineering Department .He is presently working as Deputy Manager at Alstom Transformer Research Center. His main areas of interest in R&D transformer domain are transformer modeling, noise, thermal, scientific calculations and winding technology

Stephan LELAIDIER is graduate of French engineering school Centrales Paris in 1985. He has 5 years experience in oil distribution transformers and dry type transformers R&D.

Since 10 years his career has covered all domains of Power transformers R&D, more focused on Dielectrics and special transformers as HVDC. He is currently Vice-President R&D for ALSTOM Power Transformers.

Annexe 1



BT MT HT CW FW TC

FIG. A.1 Schematic Diagram of the transformer
(BT, MT, HT: Tertiary, medium and high voltage winding; CW, FW: Coarse and Fine winding; TC - Tap Changer)

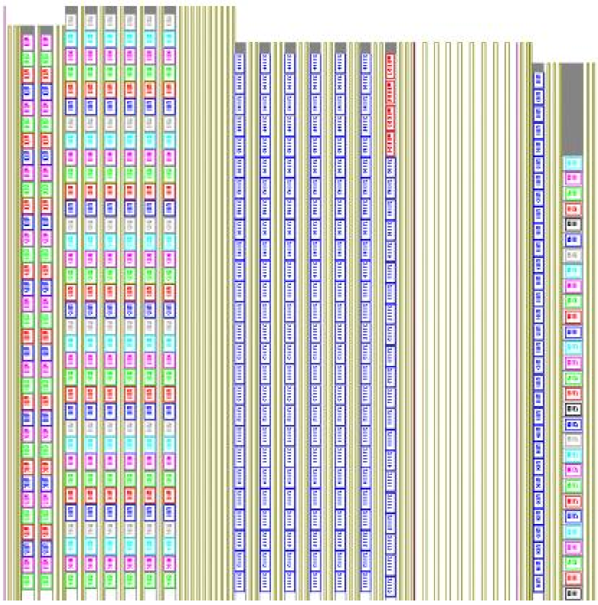


FIG. A.2 A Cross-section of the winding with few sections of the winding subdivided in the axial and radial directions. Each subdivision was analytically modeled as an inductance-capacitance network. This figure is only for illustrative purpose of the modeling concept and actual number of sub-divisions was far higher.