Using HF Lumped Parameter Model for Power Transformer Failure Investigation

J. Prins, *member, IEEE,* M. Saravolac, *member, IEEE*

Abstract: **This paper presents the conclusions of a research about the usage of computer simulation for failure investigation of a HVDC transformer. Often HVDC transformers are subjected to commutation transients. These transients can create an "envelope" of the frequency in the kHz range, which may coincide with the winding natural frequency of the transformer. The objective of this paper is to present a study of the investigation of the failure and a validation of the model by comparing the results of the lumped parameter model with measurements.**

Keywords: HVDC Power Transformer, failure investigation, modelling, and Lumped Parameter model

I. Introduction

HVDC transformers are manufactured already more than 40 years, despite years of experience HVDC transformers demands still a very high level of experience. This is mainly due to the fundamental differences between conventional transformers and conventional power transformers. These differences are mainly; insulation has to withstand combines AC and DC stresses and high harmonics distortion due to commutation transients.

Even though previous paper existing concerning HVDC transformers [2], not many papers exists where transformer modelling has been used to support the failure investigation.

This paper describes the work done on the failure investigation of HVDC transformers, which were already in service during several years.

In Figure 1, a typical failure is seen. Salient evidence of all failures are: all incidents associated only with tapping leads to the Star leg of the transformer and all flash-over happened between pairs of tapping leads, through the adjacent oil gaps.

J. Prins is with the Transformer Research Center of the Power Transformer Activity, AREVA T&D, 25 Rue des Bateliers, 93404, Saint-Ouen France. (E-mail: jan.prins@areva-td.com)

M. Saravolac is the R&D director of the Power Transformer Activity, AREVA T&D, 25 Rue des Bateliers, 93404, Saint-Ouen France. (E-mail: milan.saravolac@areva-td.com)

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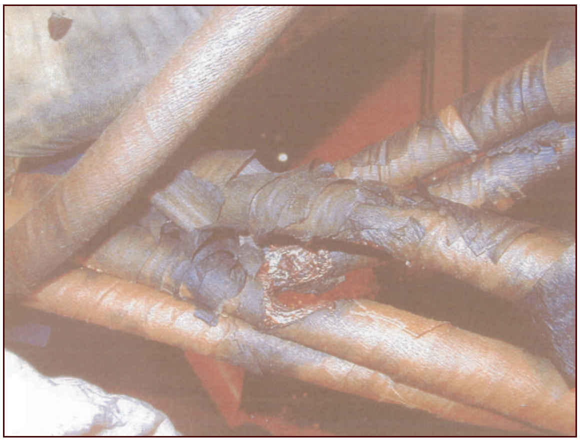

Fig.1: Flashover between tapping leads

It's believed that internal resonance could cause the flashover at tapping leads. The fact that all the failures occur on the star leg of the transformer could be associated with the fact that the tapping leads of the star leg are longer than the tapping leads of the delta leg and they're running in front of the delta leg. This configuration could change the resonance profile of the star leg to cause excessive over-voltage between tapping leads.

II. Transformer Specification

The failed HVDC transformer was a single-phase 234MVA.

Table 1: Basic design details for transformer

Rated power	234 MVA
Type	HVDC
No. of phases	Three single phase transformers
Rated frequency	50Hz
Connection diagram	Star / Delta - Star
HV rated voltages	400000±2.5%/400V
HV tap positions	23 steps with a range of +27.0 % and 6.0 %
LV rated voltages	93000 V

III. Lumped Parameter Model

The inductances and the capacitances between the winding parts define the surge voltage distribution within the transformer winding. The damping coefficient of the analysed circuit results from the losses and is integrated in the network accordingly.

A simplified model of a transformer winding is shown in figure 2; typical large power transformers have approximately thousand turns. For network investigations the winding assembly is represented by equivalent elements, also called lumped elements. An accurate calculation needs about 200 to 400 elements. Depending on the required precision, a lump element can represent one to twenty turns. The winding of figure 2 is divided in three elements, i.e.:

The equivalent resistances are integrated directly in the network during the calculation in the low frequency domain; a modal damping coefficient is used for the high frequency domain analysis.

In the high frequency domain analysis the voltages are calculated by means of the Laplace transformation, the Runge-Kutta method or by a Fourier transformation. The Gauss algorithm is applied for the low frequency domain analysis.

According to the user requirements and the chosen model precision, the voltages between different winding parts, turns and even wires are calculated and visualised.

The network model is earth free and each test arrangement can be switched according to the test requirements. The model contains following types of nodes:

- External nodes, which represent the transformer terminals
- Internal nodes, which represent on one side the tappings of the tap-changer and on the other side the nodes of the parted winding equivalent electrical network

A typical model has about 10 terminals, 30 tappings and 300 internal winding nodes. The surge voltage distribution calculation includes mainly following steps:

- Switching of required tap-changer position (internal nodes).
- Grounding of non-tested terminals (external nodes)
- Surge voltage test of respective winding.
- Visualisation and evaluation of the voltage distribution in the winding

For more information concerning the calculation method, see reference [1].

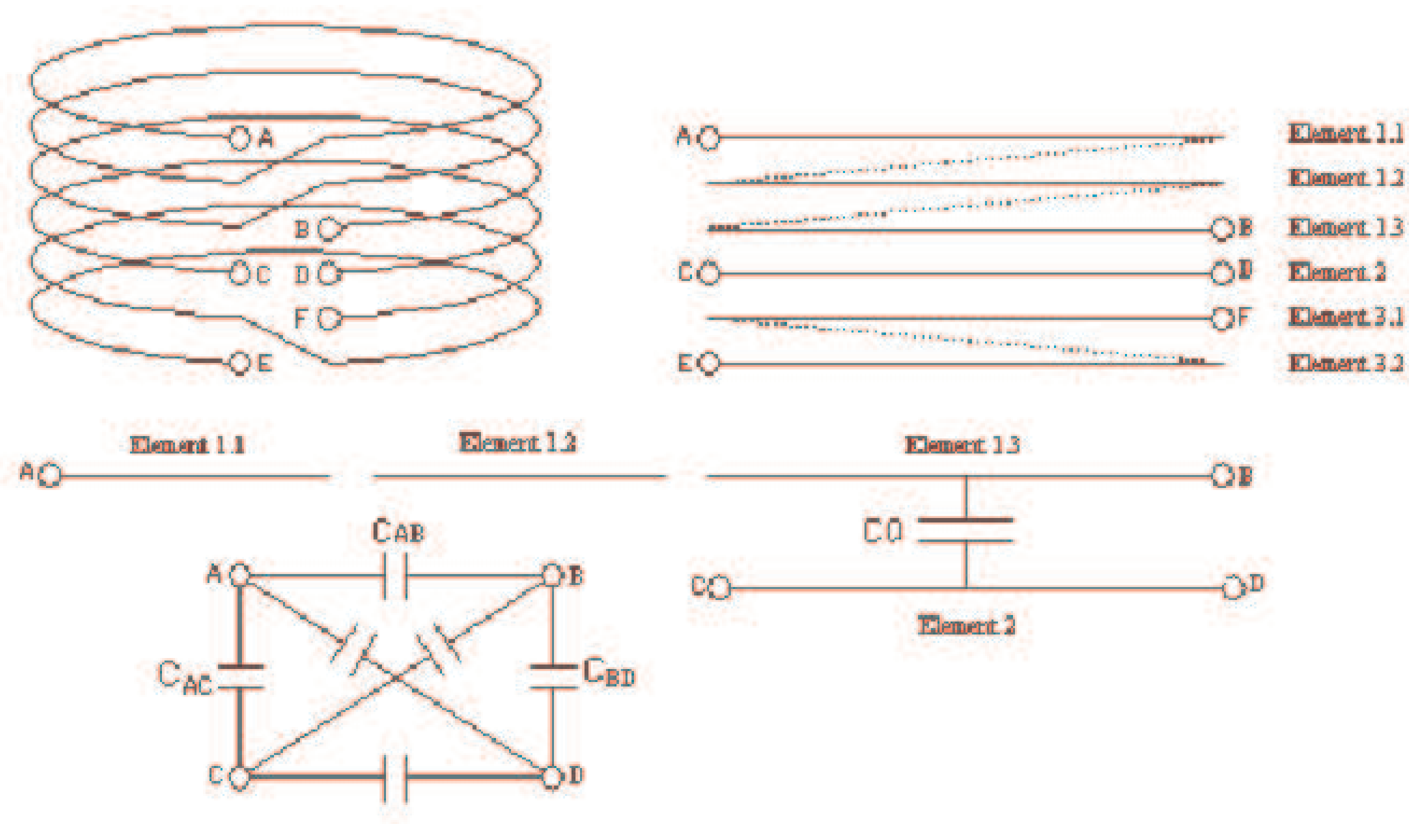

Fig.2: Model of transformer winding with equivalent circuit of capacitances

IV. Validation of Lumped Parameter Model

To support the failure analysis, the results of the RSG (Recurrent Surge Generated) measurements and Frequency Response Analysis were used to validate the lumped parameter model.

These tests were carried out on the duplicate transformer of the identical design.

V. RSG Measurements

RSG measurements are impulse measurements made at a low voltage level, these measurements are made to look at the voltage distribution along the winding and/or to verify the voltages at different tap positions. Most of the time these measurements are made before the active part of the transformer is put inside the tank.

RSG measurements have been made for several tapping positions, investigations have been concentrated on the leads where the failures occurred (See table 2).

Only the differential voltages are calculated and compared with the RSG measurement results. The focus was on the star leg.

Table 2: differential voltage (pu) for tapping lead where failures have appeared

Tap. Pos.	Lead	Calculation	Measurement
5	9 - 12	0.0490	0.0445
4	8 - 10	0.0405	-
5	9 - 11	0.0413	-
	9 - 12	0.0449	0.0445
5	9 - 12	0.0449	0.0445
2	4 - 6	0.0490	0.0630
3	5 - 7	0.0451	0.0117
14	4 - 6	0.0437	-

As most failures occurred between tapping lead 9 - 12, additional investigations have been made at between those leads (See table 3).

Table 3: differential voltage (pu) for tapping lead 9 - 12, at different tapping positions

	Calculation	Measurement
Pos. 1:	0.054	0.057
Pos. 2:	0.051	0.048
Pos. 3:	0.049	0.048
Pos. 4:	0.046	N/A
Pos. 5:	0.049	0.045
Pos. 12A:	0.087	0.104
Pos. 12C:	0.053	0.044
Pos. 14	0.052	0.044
Pos. 23:	0.060	N/A

VI. FRA Measurements

Frequency response analysis (FRA) involve the determination of the transfer function of transformer windings by applying a low voltage, typically 2V rms, sinusoidal wave of variable frequency to the terminal under test. The current input to the winding is measured at each frequency and the winding transfer function is determined by digital signal processing.

The comparison below (Figure 4 and 5) compares the FRA of the HV winding.

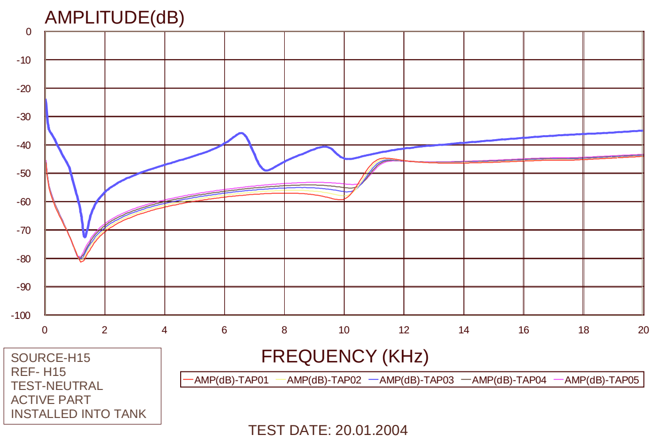

Fig. 4: FRA comparison freq. up to 20 kHz:

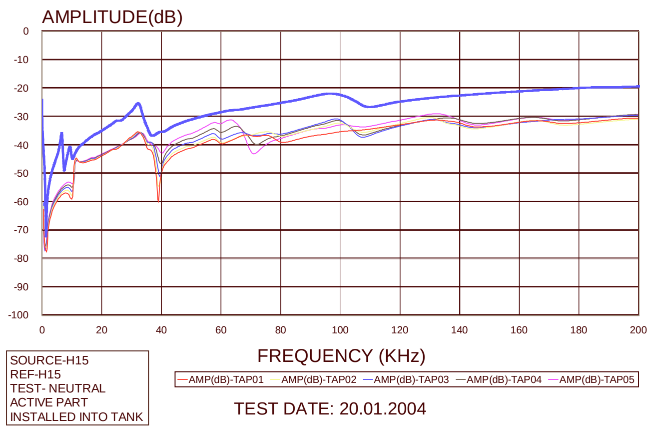

Fig. 5: FRA comparison freq. up to 200 kHz:

As seen in both analyses, the calculation and measurements show good similarity and at the RSG measurements show no evidence of high differential voltages, which could explain the failures.

VII. Failure Analyses

The failure analyses has been concentrated on the influence of oscillations and the magnitude of these oscillations at certain points. The oscillation between tapping leads 9 & 12 have been compared for injection from: valve winding, high voltage entry and high voltage neutral. Comparative analyses have been made for both star and delta legs for tapping positions: 1, 5, 12A, 12C and 23.

As the lumped parameter model has a limit of approx. 400 kHz, the calculations have been made up to this frequency.

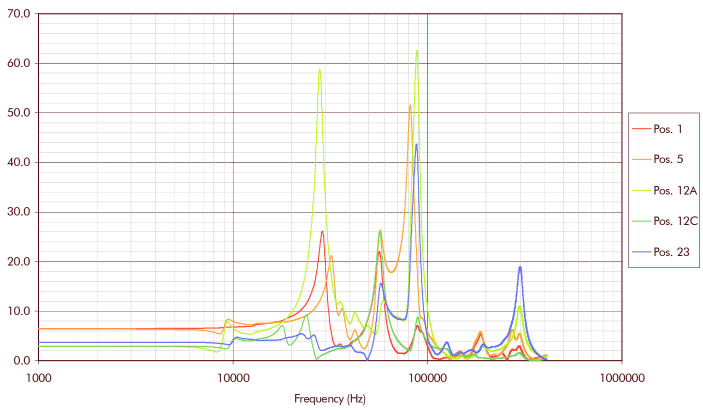

Fig. 6: Frequency spectrum analyses for tapping lead 9 -12, injection from valve winding

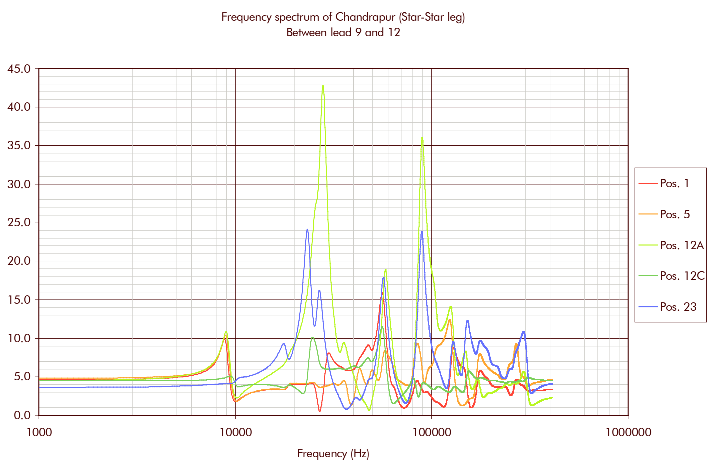

Fig. 7: Frequency spectrum analyses for tapping lead 9 -12, injection from HV winding

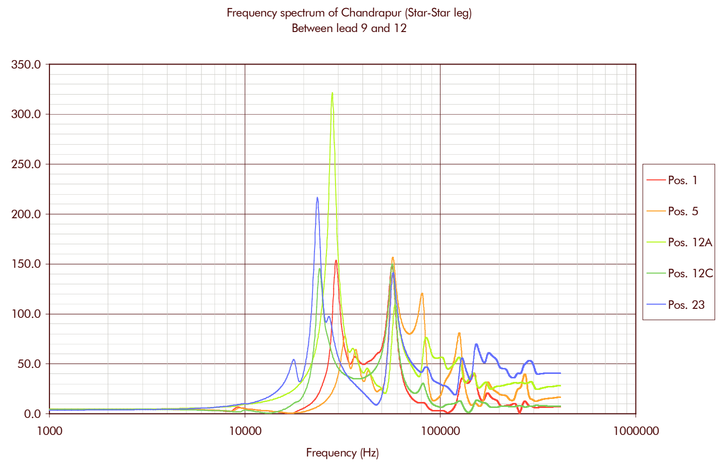

Fig. 8: Frequency spectrum analyses for tapping lead 9 -12, injection from HV neutral

In the table below, a summary is given with the comparison between different injection points and the maximum differential voltage.

Table 9: Summary table with highest differential voltages (pu) with different injection points

	RSG meas.	Valve side	HV side	HV neutral side
Tap 1	0.050	0.260	0.160	1.530
Tap 5	0.050	0.520	0.120	1.570
Tap 12A	0.090	0.630	0.430	3.220
Tap 12C	0.050	0.260	0.120	1.500
Tap 23	0.060	0.440	0.240	2.170

As seen in table 9, certain frequency ranges can cause a maximum differential voltage of 3 times the injected voltage magnitude. This proves the possibility of resonance voltages causing such high voltages that the failures occur between tapping leads.

This doesn't explain the fact that all the failures occur on the star leg of the transformer. But this could be associated with the fact that the tapping leads of the star leg are longer than the tapping leads of the delta leg and they're running in front of the delta leg. This configuration could change the resonance profile of the star leg to cause excessive over-voltage between tapping leads.

To prove this effect, we added a shunt capacitance between the tapping leads of the star-leg and the bottom leads of the tapping winding of the delta-leg. This has been done, while the leads are running through the bottom part of the tank.

Also, the capacitance between the leads and the tank has been modelled. The fact that the tapping leads are bundled together is not taken into account. The same frequency spectrum calculation as previous has been made, and the results are compared below, only the star/star and star/delta leg are compared now.

Table 10: comparison table between the star/star and star/delta leg with highest differential voltages (pu) with different injection points (f < 400 kHz)

		Valve side	HV side	HV neutral side
Tap 1	Star/star	0.34	0.23	0.35
	Star/delta	0.37	0.27	1.29
Tap 5	Star/star	0.35	0.11	1.58
	Star/delta	0.70	0.37	1.75
Tap 12A	Star/star	0.42	0.33	1.51
	Star/delta	0.57	0.30	1.17
Tap 12C	Star/star	0.24	0.18	0.64
	Star/delta	0.49	0.17	1.28
Tap 23	Star/star	0.40	0.30	1.48
	Star/delta	0.43	0.23	1.18

From the comparisons made, it's not clearly seen that there is a difference between the star and delta legs. In some cases, even the star/delta differential voltages are higher. In general it can be seen that the magnitudes have been damped, in comparison with the calculations made without the lead simulations. But in figure 11 and 12, it's seen that there is a shift in the resonance frequencies

But when we look at a frequency range up to 10 kHz it can be seen that the addition of the shunt capacitance is lowering the resonant frequencies. This means that the resonant frequencies appear closer to the harmonics at power frequencies and the differential voltage is increasing. All this can be seen as a plausible cause of the failures between the tapping leads.

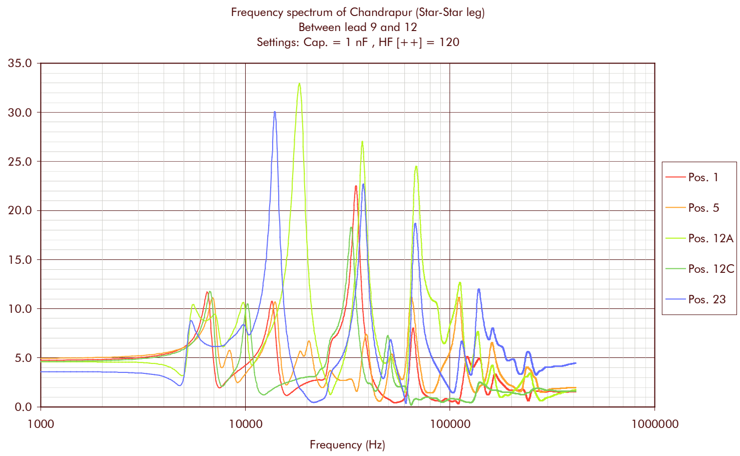

Fig. 11: Frequency spectrum analyses for tapping lead 9 -12, injection from HV winding Star/star leg

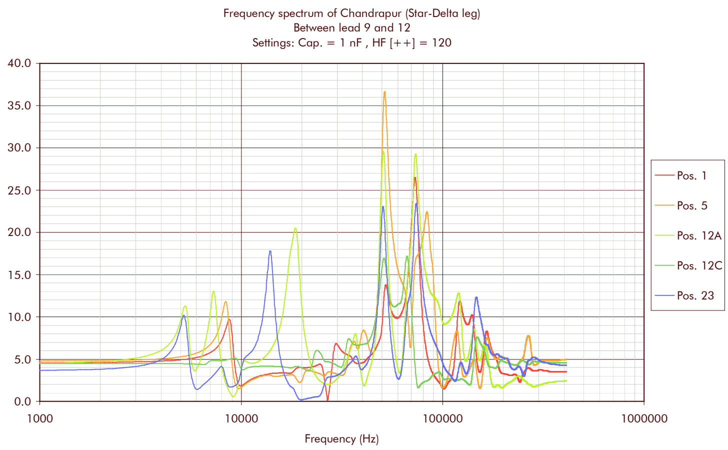

Fig. 12: Frequency spectrum analyses for tapping lead 9 -12, injection from HV winding Star/delta leg

Table 10: comparison table between the star/star and star/delta leg with highest differential voltages (pu) with different injection points (f < 10 kHz)

		Valve side	HV side	HV neutral side
Tap 1	Star/star	0.10	0.12	0.06
	Star/delta	0.07	0.10	0.07
Tap 5	Star/star	0.11	0.11	0.06
	Star/delta	0.08	0.12	0.05
Tap 12A	Star/star	0.08	0.11	0.13
	Star/delta	0.08	0.13	0.12
Tap 12C	Star/star	0.21	0.12	0.12
	Star/delta	0.04	0.05	0.04
Tap 23	Star/star	0.20	0.09	0.19
	Star/delta	0.23	0.10	0.13

VIII. CONCLUSIONS

The paper describes a detailed failure investigation of a very complex HVDC transformer. For the failure analyses a computer model is used, and the model is validated with FRA and RSG measurements.

The results of the model are in-line with the measurements. Furthermore, failure analyses have been made, and a possible cause of the failing of this transformer is found.

It's proven in the paper that resonance frequencies can cause high differential voltages between the failed tapping leads in HVDC transformers. However, as very common in this kind of analyses not sufficient information is available from the network system to analyse the exact harmonic content and therefor it's difficult to provide sufficient information to support to analyses given in this paper.

Additional it's shown that with an accurate transformer model representation, detailed analyses can be made and successful failure investigation can be made.

IX. REFERENCES

[1] P. Glaninger and B. Willy, " Calculation and visualisation of surge voltages in transformer windings", International Conference on Power Transformers, 5 September 2001

[2] K. Eckholz and P. Heinzig, " HVDC Transformers - A technical challenge", International conference on Power System Technology - PowerCon 2002, 13-17 Oct 2002