Computation of Very Fast Transient Overvoltages inside Transformers resulting from Switchings in Power Plants

O. Moreau[(1)], G. Dos Santos[(2)], Y. Guillot[(3)]

Abstract—Generator-Step-Up (GSU) transformers in pumped storage plant are particularly subject to frequent routine switching operations involving Circuit Breakers (CB) and Disconnector Switchings (DS). Resulting internal Very Fast Transient Overvoltages (V.F.T.O) in transformer windings generate dielectric and mechanical stresses inside their windings. Therefore, as much for damage survey as intending specifications improvements in the fields of design, standard tests and switching operations, a numerical tool has been developed to predict the transient electrical behavior inside a transformer: SUMER. Using EMTP network software for modelling the substation and a part of the grid, dielectric stress inside operating transformers connected to a Gas Insulation Substation (GIS) have been computed and compared to the response implied by the standard tests now in force.

Keywords: Electromagnetic transient analysis, Very Fast Transient, Generator-Step-Up transformer, Gas Insulated Station, Finite Element Method.

I. Introduction

HIGH frequency modelling is used at EDF R&D to predict Very Fast Transient Overvoltage in transformer windings resulting from events in the power system [1] and to interpret FRA (Frequency Response Analysis) measurements with regard to transformer diagnosis [2]. SUMER software, developed at the R&D division of EDF, is dedicated to derive HF transformer models, compatible with EMTP software [3], from manufacturer data (geometry, material characteristics).

Generator-Step-Up (GSU) transformers in pumped storage plants are subject to frequent routine switching operations, which generate dielectric and mechanical stress inside their windings. As a matter of fact, frequent unit starts and stops implying opening and closing of Circuit Breaker (CB) and Disconnector Switching (DS) are specific characteristics in pumped storage plants. Resulting Very Fast Transient (VFT) at GSU transformer terminals may affect, specially in a Gas Insulated Substation (GIS), transformer insulation, and lead to possible failures. So, they have to be taken into account to improve current technical specifications, and switching operations now in force. This study has been performed using SUMER for transformer modelling and EMTP software for the substation and grid parts.

II. SUMER Modelling

The adopted approach consists in modelling a wounded material as a network of lumped RLC elements. R, L C coefficients stand for the magnetic and dielectric couplings between groups of turns (denoted *electrical element*) of the windings. Let us consider the imaginary shell-type transformer of Fig.1. *Hereafter in the paper the main notions will be defined by keywords written in italic.*

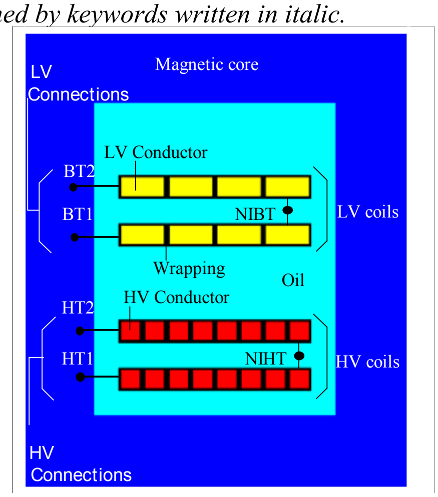

Fig. 1. Imaginary shell form transformer (2D view)

A. Electrical discretisation

For that purpose, the first step is to generate an *electrical mesh* of the transformer by discretising its windings into *electrical elements*. Their electromagnetic properties (self and coupled capacitance, inductance, dielectric and magnetic losses) are modeled by elementary Π cell circuits (Fig. 2 and 3).

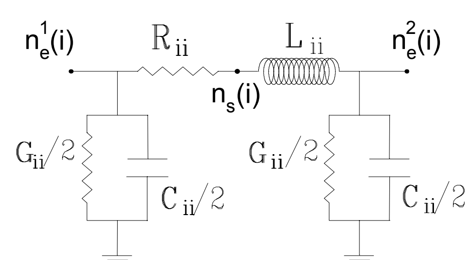

Fig. 2. Self effects

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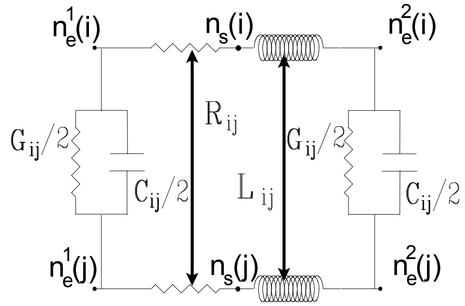

Fig. 3. Coupling effects

As such a modelling requires a quasi linear voltage variation along the *electrical element*, the *electrical* (spatial) *mesh* possesses a cutoff frequency. So it is essential that the longest group of turns represented by one *electrical element* should be much shorter than the shortest wavelength of the investigated frequency bandwith. The more the length of the longest *electrical element* is small with regard to the shortest wavelength, the more the *electrical mesh* is accurate.

The R_{ii} term stands for the ohmic losses due to both the self-skin effect in the supplied *electrical element i* and the eddy currents loops the latter induces in all the opened *electrical elements j* ($j \neq i$) as well as in magnetic sheets. On the other hand, the R_{ij} term only expresses the fact that the induced voltage of the opened *electrical element j* is not in quadrature with respect to the current in the supplied *electrical element i*. This phenomenon is due to the eddy currents loops developing in every conductive material (magnetic core, electrostatic shields and conductors). Moreover eddy currents in conductive materials implies a frequency dependence for R and L coefficients. In addition R and L (respectively C and G) terms can also depend intrinsically on the frequency if permeability (respectively permittivity and dielectric loss factor) varies according to frequency.

Considering a pancake discretisation (Fig. 2) for the test-case (Fig. 1) leads to 4 *electrical elements* (HT1, HT2, BT1, BT2), four terminals connections (BT1, BT2, HT1, HT2) and two internal nodes (NIBT, NIHT).

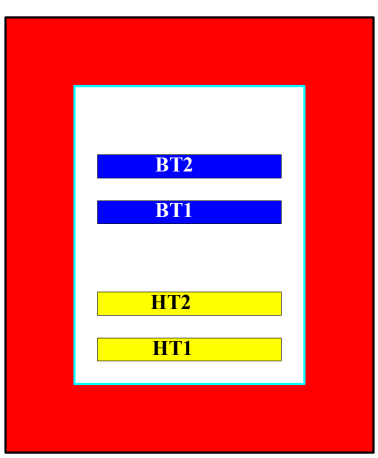

Fig. 4. Pancake discretisation

The assembling of elementary Π cell circuits, according to the connecting mode, leads to the *network model* of the Fig. 5.

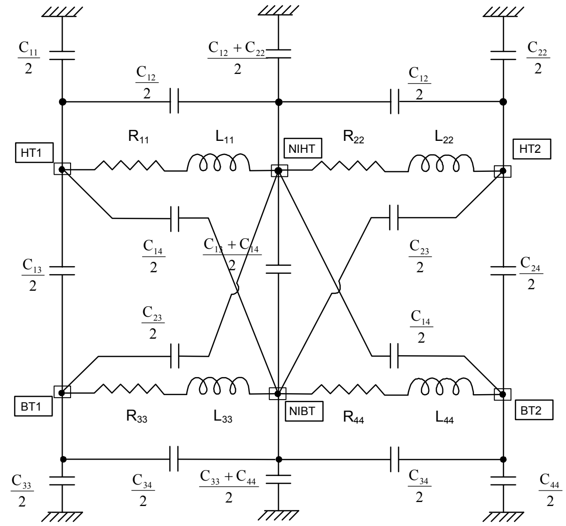

Fig. 5. Network model for a pancake electrical mesh (magnetic couplings not depicted)

B. *R, L, C and G computation*

The evaluation of these RLCG parameters at high frequencies (up to several MHz) are performed with the finite element electromagnetic field computation softwares FLUX2D[4] and FLUX3D[5]. This choice enable us to take into account realistic geometries and accurate material models for eddy current losses computing in the conductors (proximity and skin effect) and magnetic core.

1) C and G computation

Assuming n *electrical elements*, capacitance and conductance $n \times n$ matrices derive from n resolutions of (1) with a complex permittivity ε^* ($\varepsilon^*(\omega)=\varepsilon'(\omega)-j(\sigma/\omega+\varepsilon''(\omega))$):

$$div\left(\varepsilon^* \, \mathbf{grad}\, V\right) = 0 \qquad (1)$$

2) L and R computation

In the same way inductance and resistance matrices are achieved by n resolutions of (2) involving a complex permeability μ^* where *electrical element i* ($i= 1,..,n$) is supplied with a current density source **J**.

$$\mathbf{curl}\left(\frac{1}{\mu^*}\mathbf{curl}\,\mathbf{A}\right) = \mathbf{J} \qquad (2)$$

Standard FEM eddy currents computation remains unfortunately unfeasible in actual electrical devices, specially at high frequencies. As a matter of fact, taking properly skin effect requires at least two finite elements in the skin depth which would involve unrealistic meshes. For induced currents accounting (proximity effects), complex permeability method applied to windings, electrostatic shields and magnetic core makes it possible to approximate R and L matrices without computing the eddy currents. The approach consists in substituting a non conductive ferromagnetic material, featuring an elliptical loop described with a complex permeability, for a conductive material (Fig. 6). Frequency dependent ohmic losses and field shielding effect resulting from eddy currents are therefore derived from an equivalent hysteresis behavior [6].

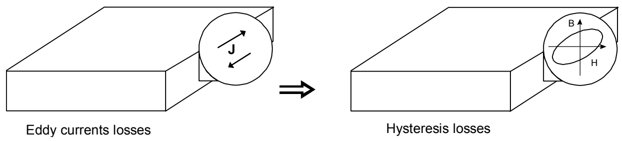

Fig. 6. Complex permeability principle

3) Self conductor losses

Assuming the separation of self and induced effects, the accounting of the losses due to self-skin effect in conductors needs a self-resistance and inductance term [7] be added to the diagonal terms of the R and L matrices computed with the FE software

C. Modal analysis

According to the block decomposition of the admittance matrix with regard to the internal nodes (i) and the connection nodes (l), the Ohm law related to the *network model* can be written as:

$$\begin{bmatrix} Y_{ll} & Y_{li} \\ {}^{t}Y_{li} & Y_{ii} \end{bmatrix} \begin{bmatrix} V_l \\ V_i \end{bmatrix} = \begin{bmatrix} I_l \\ 0 \end{bmatrix} \tag{3}$$

which leads to :

$$\begin{cases} -Y_{ii}^{-1}\,{}^{t}Y_{li}V_l = V_i \\ \left[Y_{ll} - Y_{li}Y_{ii}^{-1}\,{}^{t}Y_{li}\right]V_l = I_l \end{cases} \quad \text{i.e.} \quad \begin{cases} V_i = HV_l \\ \widetilde{Y}V_l = I_l \end{cases} \tag{4}$$

with :

- H : *transfer matrix,*
- $\widetilde{Y}$: *condensed admittance matrix.*

$\widetilde{Y}$ can stand for a frequency signature of the transformer. The determination of the matrices $\widetilde{Y}$ needs the formal expression, with regard to the Laplace operator p, of the internal impedance Y_{ii}. This will be achieved by *modal analysis* which consists in searching the eigenvalue-eigenvector couples of the dynamic operator $Y_{ii}(p,\omega)$. Finally we obtain [8]:

$$\widetilde{Y} = p\widetilde{C} + \widetilde{G} - \sum_{n=1}^{n_e} \frac{I_n p + J_n}{p^2 + \gamma_n p + \delta_n} - \sum_{n=1}^{n_r} \frac{K_n}{p + \mu_n} \tag{5}$$

$$H = H^{stat} - \sum_{n=1}^{n_e} \frac{pL_n + M_n}{p^2 + \gamma_n p + \delta_n} - \sum_{n=1}^{n_r} \frac{N_n}{p + \mu_n} \tag{6}$$

where $\widetilde{C}, \widetilde{G}$, In, J_n, and K_n involve Y_{ii} matrix terms and results of *modal analysis* [8]. Moreover, $\widetilde{Y}$ can also be synthesized in a RLC element circuit called the equivalent *multiport circuit* depicted in Fig. 7 for the test-case transformer where each *multiport circuit* branch has the topology shown in Fig. 8.

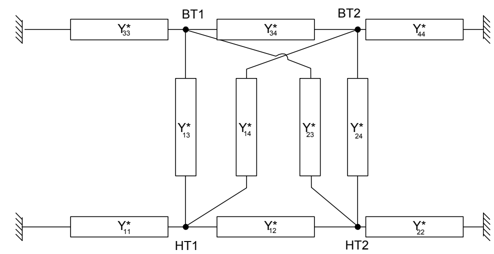

Fig. 7. Multiport circuit for the test-case

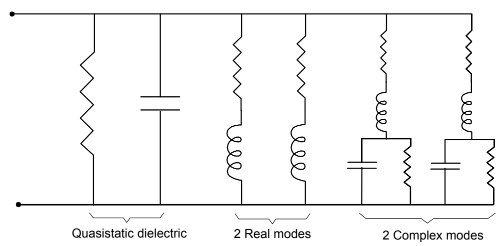

Fig. 8. Multiport circuit branch for the test-case

D. Internal responses

The expression of the internal responses coming from (6) is :

$$V_i = H^{stat}V_l + \sum_{n=1}^{n_e} H_n^c V_l + \sum_{n=1}^{n_r} H_n^r V_l \tag{7}$$

So the responses in the time domain at the *internal node p* is written as (* means convolution product) :

$$v_{i,p}(t) = \sum_{q=1}^{q=n_l} h_{p,q}^{stat} v_{l,q}(t) + \sum_{n=1}^{n=n_e}\sum_{q=1}^{q=n_l} h_{n,p,q}^{c}(t) * v_{l,q}(t) + \sum_{n=1}^{n=n_r}\sum_{q=1}^{q=n_l} h_{n,p,q}^{r}(t) * v_{l,q}(t) \tag{8}$$

with :

$$h_{n,p,q}^{c} = \frac{\alpha_{p,q}^{n} p + \beta_{p,q}^{n}}{p^2 + \gamma_n p + \delta_n} \quad \text{and} \quad h_{n,p,q}^{r} = \frac{\nu_{p,q}^{n}}{p + \mu_n} \tag{9}$$

1) complex contribution

Each contribution $x(t) = \left[h_{n,p,q}^{c} * v_{l,q}\right](t)$ related to the *q-th connection node* potential and to the *n-th* complex mode is interpreted as the solution of the following second order Ordinary Differential Equation (ODE) under steady state initial conditions.

$$\ddot{x} + 2\varepsilon_0\omega_0\dot{x} + \omega_0^2 x = \alpha_{p,q}^{n}\dot{v}_{l,q}(t) + \beta_{p,q}^{n} v_{l,q}(t) \tag{10}$$

The ODE (10) is solved by the usual way of the Duhamel's integral.

2) real contribution

Each contribution $x(t) = \left[h_{n,p,q}^{r} * v_{l,q}\right](t)$ related to the *q-th connection node potential* and to the *n-th* real mode is interpreted as the solution of the first order ODE (11):

$$\dot{y} + \mu_n y = \nu_{p,q}^{n} v_{l,q}(t) \tag{11}$$

solved by the same method as for the complex contributions.

III. Transient computation in Gas Insulation Station

A. GIS and Transformer description

1) GIS

The GIS operates as a double bus with a coupling system. Two overhead line departures may be connected to the two bus bars. All the six special 400kV three phase transformers may be connected to each of the two bus bar via coupling DS. Two of them are connected to two turbines whereas the others are associated to two reversible units each.

2) Transformers

The six GSU transformers of 340MVA/400kV/15,5kV are all of three phase core-type with pancake interleaved HV coils, and layer LV coils.

B. Modelling hypothesis

1) Transformer

This study involving steep front surges has required a transformer model accurate up to 3MHz. This frequency validity domain has implied one *electrical element* for two turns which has led to 371 *electrical elements* for a single phase. Such a model size has compelled us to neglect the phase coupling by considering three single phase models instead of one three phase model. Moreover, for a matter of CPU consuming, 2D modelling has to be used for matrix computation. On one hand, 2D plane geometry hypothesis has been applied at low frequency to take into account the magnetic core. On the other hand, 2D axisymetrical geometry could be used at High Frequency assuming a complete shielding of the magnetic core (Fig. 9). R and L matrices have been computed for a twenty frequencies sampling.

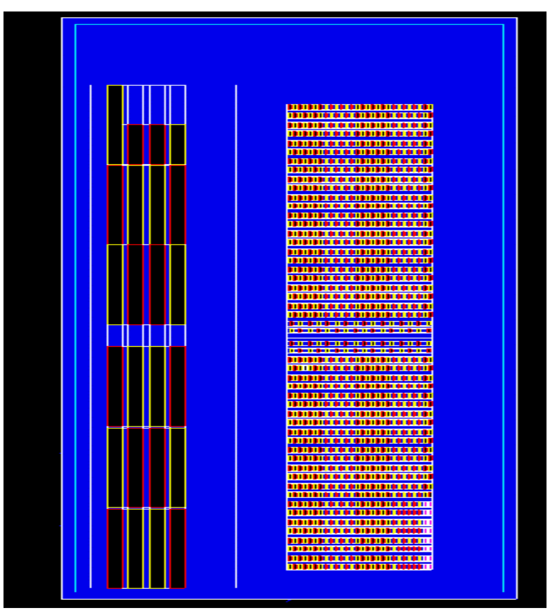

Figure 9. Core type transformer (2D view of a half single phase)

The model has been validated with FRA measurements carried out on site (Fig 10 and 11). Simulations show good accuracy for eigen frequencies but an underestimated damping leading to overestimate the resulting internal potentials.

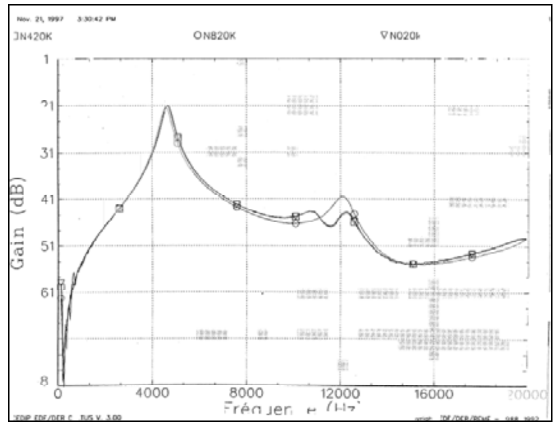

Fig. 10. FRA experimental measurements

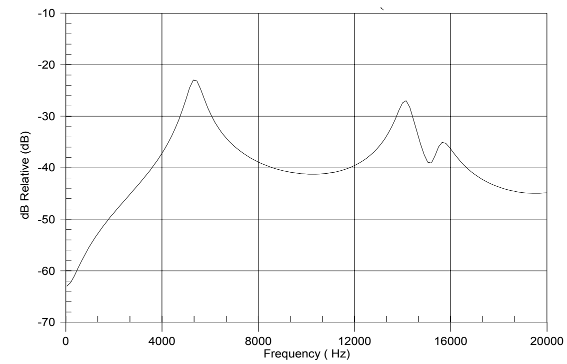

Fig. 11 FRA measurement simulation

2) GIS

Modelling of GIS components and electrical equipment can be found in [9]. Nature and value describing the different components are given in Table I.

TABLE I
GIS COMPONENT MODELS

COMPONENT	EQUIVALENT CIRCUIT AND VALUE
GIS bus bar	EMTP model : “CABLE CONSTANT”
Power transformer	SUMER model “3MHz”
CB	PI circuit with capacitances (120pF to 200pF)
DS	PI circuit with capacitances (20pF to 25pF)
Earth switching	Capacitance : 40pF
Voltage transformer	Capacitance : 100pF
Current transformer	Capacitance : 4nF
Bushing	Capacitance : 100 to 183pF

General adopted hypothesis are presented below:

- Only the surge transients generated by circuit breaker switching connected at GSU transformers in GIS have been considered,
- For CB switchings, single phase closings have been considered,
- The CB closing is applied on peak potential value, therefore it corresponds to the most unfavourable case,
- In order to compare overvoltages, the simulation time for the different switching operations has been

defined at 30µs with a step time at 15ns (minimal step time value imposed by the bus bar modelling).

- The overvoltage transients problem in GIS [~100kHz to 10MHz range] has required to define the HF behaviour (capacitance dominating) of each components in GIS (Table 1)

C. Transient overvoltages at GSU terminal connections

The first part of the study has consisted in computing and analyzing overvoltages at High Voltage GSU transformer terminals in GIS generated during different CB switching.

Analysis of routine CB switching shows the following points :

- Maximal overvoltage levels don't exceed 1.36p.u.
- Steep front potential values given in rate of rise (dV/dt) don't exceed 500kV/µs
- Oscillations located at 700kHz and 3MHz have been found

However, the Basic Impulse Lightning (BIL) value for this transformer is 1425kV (~4.15pu and 1200kV/µs). Therefore, computation results show that no overvoltage exceeded the BIL condition. It remained to evaluate the stresses resulting from the 700kHz and 3MHz resonances.

The internal potential distribution along transformer windings is obtained using the results of previous EMTP simulations. Internal potential analysis has concerned specified and/or recommended tests by the CEI 76.3 standard, and usual switching operations applied in the plant.

IV. Internal potential along transformer windings for BIL test

To make the understanding easier, only the BIL test simulation case is presented in detail. The simulation consists in applying to GSU transformer line terminal the standard wave 1.2/50µs with a peak value of 1425kV. The other terminals are connected to earth. Previous SUMER transformer model has been inserted in an EMTP network standing for the test platform. Internal potential concerning HV coils provided by SUMER are given in Fig. 12:

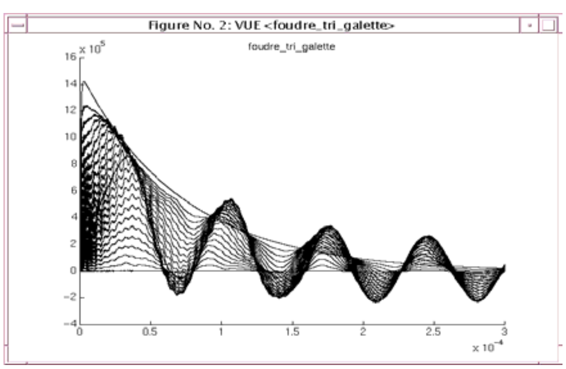

Fig. 12. Internal potential distribution (BIL test)

Fig. 12 shows internal potential on nodes located between HV winding coils. X axis gives time in seconds, and Y axis potential value with regard to ground in volts. It can be noticed that oscillations are superposed to the injected signal (bi-exponential wave). We can observe a major oscillation of about 14kHz corresponding to the transformer first eigenmode, and higher than the initial oscillations. Potential on nodes give a behaviour criterion of main transformer insulation regarding earthed tank and screens.

V. Comparison between BIL and operating overvoltages

In order to provide some help in the wave shape analysis and interpretation, specific post-processing is available in SUMER to get:

- **maximal potential values** and corresponding **rate of rise (dV/dt)** on each internal node defined by *electrical mesh*,
- **potential difference maximal values** between each coil part

As a general rule, the analysis methodology is based on the wave shape comparison between values applied during the operating condition in the plants and the test values specified or recommended (BIL, Induced-Voltage test, Low Frequency test). Test values specified by CEI 76.3 standard are supposed to "cover" these obtained during operation condition.

So, for every node located between HV pancake, Fig. 13 shows a comparison between maximal potential values generated during the BIL test specified "wave 1,2/50µs" and those obtained during three CB switching in GIS. In addition, Fig. 14 shows the rate of rise (dV/dt) comparison for the same simulations.

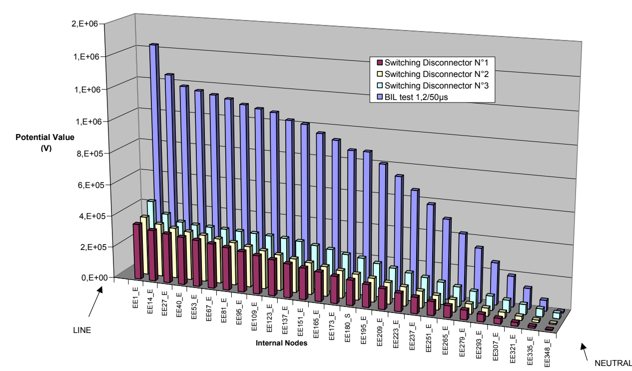

Fig. 13. Maximal potential values comparison

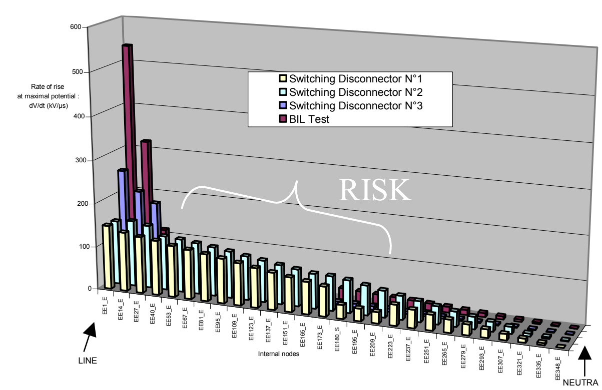

Fig. 14. Rate of rise (dV/dt) comparison

As an important result, maximal potential values computed for specified BIL test with 1.2/50µs wave are significantly higher than those obtained from operating switching in the plant. However, **some values of rate of rise obtained during switching routine operations are higher than those resulting from the specified BIL test**.

VI. Conclusion

SUMER software is currently used at EDF to interpret FRA (Frequency Response Analysis) measurements and to predict Very Fast Transient Overvoltages inside transformers due to events in the power system. A high frequency transformer model for the EMTP software is derived from manufacturer data thanks to finite element electromagnetic field computation and numerical modal analysis.

Applied to different CB switchings operations happening to Generator-Step-Up (GSU) transformers in a GIS, numerical simulations have shown :

- Steep front surges and VFT excite HF resonance inside transformer windings, but do not affect the main insulation,
- Internal stress generates no overvoltage exceeding the main transformer insulation,
- Post-processing shows hazards due to rate of rise (dV/dt) stress generated during routine switching operations not covered by specification tests (BIL, Induced-Voltage test, Low Frequency test),
- On the other hand, chopped wave tests may cover the dV/dt values not covered by the full wave, if time up to the cut is smaller than 4µs, and the front during the cut is steep enough.

Finally, this test-case made it possible to point out that:

- Cases do exist in which main transformer insulation is not covered by the test values specified,
- Modelling tools do exist that can really help Power System managers to quantify hazard factors

VII. References

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VIII. Biographies

Olivier Moreau was born in Nantes, France, on June 2 1965. He received his Electrical Engineering diploma of the Polytechnic Institute of Grenoble (INPG) in 1989. Then he joined the Electricite de France Company (Electrical Equipment department at the Research and Development Division) in 1992 as a research engineer mainly involved in high frequency modelling and static electrification phenomenon in power transformers. He passed his Ph.D. degree in electrical engineering in 2003. He has published about 30 conference and journal papers and belongs to the Society of Electrical and Electronics Engineers (SEE) in France.

Yves Guillot was born in Paris, France, on April 1 1967. He received his Electrical Engineering diploma of the Ecole Supérieure d'electricité (Supelec) in 1990. Then he joined the Electricite de France Company (Electrical Equipment department at the Research and Development Division) in 1991 as a research engineer mainly involved in transient modelling in power systems. He has published about 10 conference and journal papers.

G. Dos Santos was born in Reims, France, on August 7 1970. He joined the Electricite de France Company (Electrical Equipment department at the Research and Development Division) in 1992 as a research technician in the Laboratory of Tests of Rotating Machines in Saint-Denis, France. Then, he passed an Electrical Engineering diploma of the Technology University of Compiègne (UTC) in 2000. Then, he is in charge of studies mainly involved in high frequency modelling and overvoltages computations in power transformers. He joined the Gaz de France Company (Corrosion department at the Transport Direction) in September 2004 as engineer involved in cathodic protection on the pipelines