Validation of power plant transformers re-energization schemes in case of black-out by comparison between studies and field tests measurements

François-Xavier ZGAINSKI, Bruno CAILLAULT, Vincent-Louis RENOUARD

Abstract-- The EHV network and power plant restoration plan is a key process of a fast re-energization of customers.

The first step after a black-out consists in re-energizing lines and transformers, both on the network and in power plants, as soon as possible, without taking too much risks. To validate the strategy based on identified schemes, the following methodology is detailed: first the critical point to deal with is the evaluation, by using computation tools, of the temporary harmonic overvoltages generated by the transformer re-energization. If the conclusion is positive, field tests are performed. Finally, measurements are compared with simulations results in order to validate the initial feasibility study.

Keywords: black-out, transformer re-energization, field tests.

I. INTRODUCTION

After a black-out, an initial energizing step is required before completely restoring the electrical power to consumers. Very weak networks can be used to re-energize, through unloaded EHV lines, one or more other power generating units. The first steps may consist in:

- identifying the power plants islanded, that can be used to restore power to those out of power in order to secure them in priority,
- re-energizing the auxiliary transformers of the power plants out of power, and supplying the auxiliaries,
- re-connecting as soon as possible power plants together through EHV lines, and supplying the load.

The main problems encountered during the first step of re-energizing transformers are steady state and transient overvoltages that can damage electrical devices connected to the network to restore.

The following figure gives an example of topology of the studied network schemes.

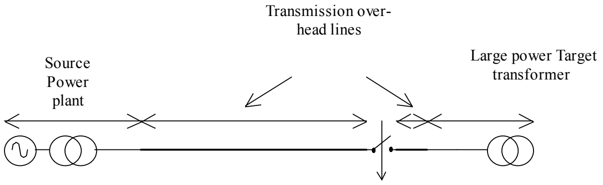

Fig. 1. Network configuration studied in the case of transformer switching

The source power plant is a large power plant generally connected to the 400kV network and is used to re-energize an auxiliary transformer. EHV lines are 50 kilometers long, and in some cases can reach 250 kilometers. It must be necessary sometimes to re-energize firstly an intermediate network transformer.

In the case presented hereafter, a large network transformer (3x357 MVA) has been switched on, located at 50 km of a 900 MW power plant. EDF has experience on several schemes where 96 MVA auxiliary power plant transformers are switched on, with both studies and field tests, but it was the first time in France that such a large transformer was re-energized with such a network.

II. EVALUATION OF THE TEMPORARY HARMONIC OVERVOLTAGES

The energization of power transformers may create saturation of the transformer magnetic core and can lead to large harmonic temporary overvoltages due to high inrush currents. Key parameters for the analysis of such overvoltages are the following ones :

- The resonance frequency of the network;
- The losses of the network, dependant on its resonance frequency, and the load connected to the network;
- The saturation characteristic of the transformers feeded by the network;
- The voltage level at the end of the EHV lines.

In order to minimize both steady state and transient overvoltages, the setting point of the source power plant automatic voltage regulator is reduced to its minimum value, i.e. usually 0.9 p.u.

Furthermore, the levels of overvoltages and inrush currents depend also on the initial conditions of the switching :

- closing times of the circuit breaker poles;
- remanent fluxes in the core of the transformer to switch-on.

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A. Description of the modeling of the network

The electrical components of the network are modeled using the EMTP tool.

The generator is represented by a perfect voltage source with a resistance and an inductance that are obtained by a computation based on the sub-transient values of the inductance and of the time constant. This simplified model is adapted for [100Hz-500Hz] frequency range resonances [7]. Its simplification is compensated for by taking into account uncertainties on the value of the inductance (see section B).

The line sections are modeled by using matrix PI section model that deals with both electrical and magnetic coupling between each electrical conductor. One PI section is used for every 25 kilometers line section. In order to represent the losses, parameters are calculated at the network resonance frequency. A good geometrical description of the over-head line towers is provided.

The transformers are described by three single phase transformers, described by a classical model shown on the following figure, that takes into account the iron losses, the resistances of each conductors, and the short circuits values of the transformer.

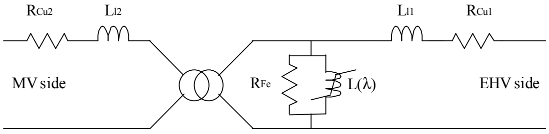


Fig. 2. Transformer model used in this study

The non linearity of the transformer magnetic core is modeled by a non linear inductance - characterized by a curve of the flux versus the current (flux(I)) – put in parallel with the iron loss resistance. For the target transformer, hysteresis is added, in order to take into account the remanent fluxes in the iron core. Each pole of the circuit breaker is represented by an ideal switch in order to statistically modify the different closing times of each pole.

B. The methodology defined for the studies

The simulations are made to check that the overvoltages levels and durations stay under the admissible limits given by the constructor, or, if not, within limits and proportion judged acceptable, considering the strategic importance of the transformer, situated in a power plant or on the network, and considering the potential different solutions existing for re-energizing it.

In order to take into account the uncertainties on the key parameters of the network, a large number of computations have to be performed.

All the modeling and simulation hypothesis result from discussions with EDF-R&D about the study methodology [4] and from the comparisons made between computations and field tests data.

First of all, the inductance of the generator is taken as a +/- 15% value around the direct-axis sub-transient reactance value (X"d). The phase-to-earth capacitance of the over-head lines ($C_{\varphi/t}$) is supposed to be known at +/- 5%. It hasn't been possible yet to reduce these uncertainty ranges, because of the differences still remaining between simulations and field tests measurements (see part III section C).

In order to consider the uncertainty domain corresponding to these two parameters, which have an influence on the network resonance frequency value, 25 couples of values are defined. Each couple has the same probability to fit with the real value, and is thus associated with a network frequency value, which proximity with an harmonic of the 50Hz will lead to particular resonances.

For each couple defined, 100 computations are done statistically to deal with the random switching initial conditions: closing times of the circuit breaker poles, and remanent fluxes in the transformer core.

These initial conditions are considered as random conditions because they can not generally be imposed and controlled. We use measurements in order to have an idea of their extreme values and apply random laws on these conditions. The closing times rules are the following ones : the first pole of the circuit breaker is closed anytime on one time period, and the second and third pole are closed with a standard deviation of 20 ms (i.e. one period of 50Hz). The remanent flux values follow a uniform distribution, and are supposed to reach 0,8p.u. [7]; due to the winding delta connection always present in the power plant or network transformers considered, the sum of the three remanent flux values is assumed to be equal to zero.

The saturation curve, and especially the Lsat i.e. the final slope of this curve, is a key point for the computation of the inrush currents but is not very easy to obtain. The transformer manufacturer provides a Lsat slope value with a dispersion usually considered of +/-20 %. The lower value is taken in the simulations.

The results of the computations are the estimated probability to get overvoltages higher and longer than the limits prescribed. The voltages and currents curves are also analyzed to verify the realism of the computations, as illustrated below.

C. Results of simulations

The following figure gives the simulation results obtained in one of the worse cases computed at the switching of the transformer.

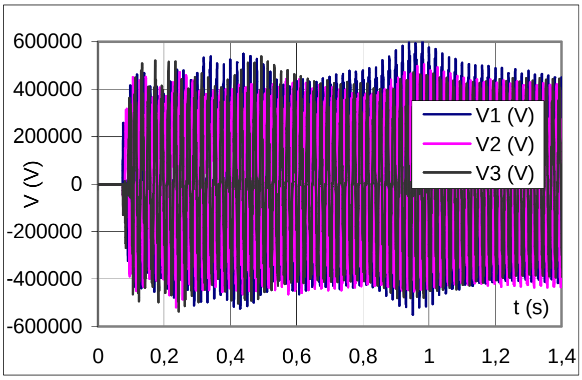


Fig. 3. Three 400kV phase to earth voltages simulated in one case.

The currents and the voltages signals can be distorted during several seconds. A natural frequency resonance is superimposed on the fundamental frequency because of the resonance between, on the one hand, the inductance of the generator and the non linear inductance of the transformers, and, on the other hand, the capacitance of the lines. If the resonance frequency is close to an harmonic of the 50Hz, the switching can lead to high resonances, during several seconds (see fig. 4).

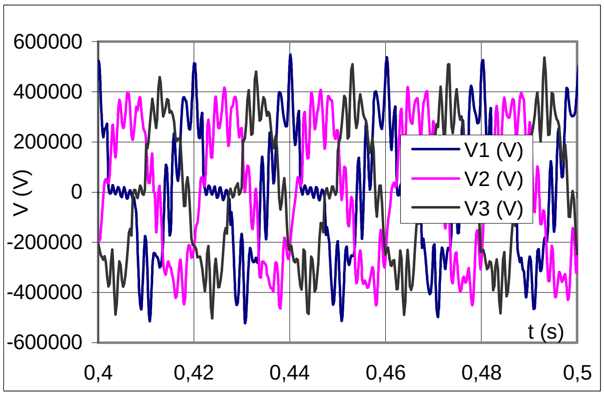


Fig. 4. Zoom on the temporary overvoltages of V1.

The peak voltage values may reach or exceed 2 p.u.

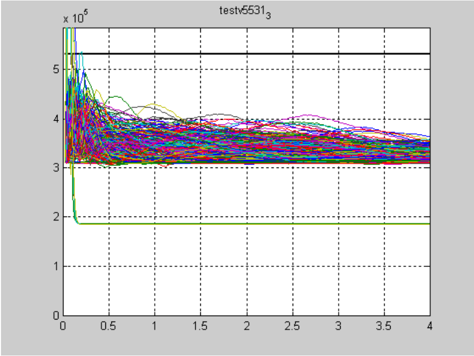
The resonance and therefore the risk of high and long overvoltages on the transformers connected on this “weak” network depend on the network parameters : the direct-axis sub-transient reactance (X''_d) of the generator and the phase-to-earth capacitance of the over-head line($C_{\varphi/t}$).

The frequency depends of course on the length of the line and on the type of source power plant, but also on the shunt reactor that can be connected. In our cases, the frequency values of the networks that are considered stand between 150 and 500 Hz. Thus, the 3rd to the 10th harmonics are in the frequency spectrum of the networks studied and can be excited by the re-energization of the transformer.

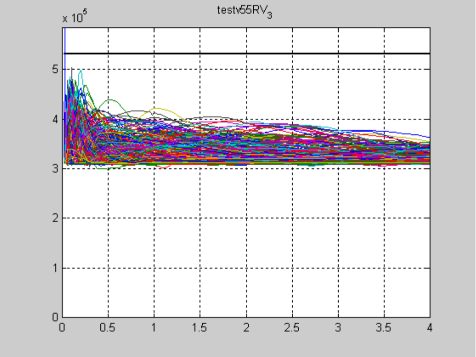
D. Comparison of the 2 versions of EMTP for the modeling of transformer switching

We are now using both EMTP 3.1 [1] and EMTP-RV [2], and trying to analyze the differences in the models of these two codes : the main problem concerns the hysteresis model that is used for the target transformers. Some work has been done on the parameters values needed in the EMTP-RV model in order to fit with the original curve flux(I) used in EMTP 3.1, but their determination remains quite difficult due to the few data provided by the manufacturers.

In order to compare simulation results between these two software, we have drawn the following figures that show the waves of the peak values of the phase-to-earth voltages for 100 simulations computed, which gives 300 curves for each computation (one per phase).



EMTP-3.1 (300 curves)



EMTP-RV (300 curves)

Fig. 5. Peak values of the voltages simulated on 4 seconds for 100 simulations with the 2 codes : EMTP-3.1 and EMTP-RV

It can be also underlined that the minor loop parameters in the hysteretic reactor model of EMTP-RV [5] have to be optimized in order to compare with the EMTP 3.1 version. With these fittings, a good agreement was found between the two codes. It can be noted that EMTP-3.1 can be less stable than the new version: in fig 5, one case simulated –i.e. corresponding to one set of initial conditions- with EMTP-3.1 must be analyzed and verified with other computation parameters.

III. FIELD TESTS AND MEASUREMENTS

Field tests are performed in order to check the studies done with EMTP. Measurements of voltages and currents are performed during the tests.

A. Main objective of the measurements on the network and general considerations

When transformer is switched on, we have to check that the overvoltages stay under the admissible limits given by the constructor. Also, particular attention is kept on the presence of harmonics. In case of emergency, we have to alert the network operator and switch off the transformer supplied as quickly as possible.

The following figure shows the location of the measuring points and the sampling rate chosen for the data acquisition during the tests. Four teams are located along the network in order to measure and get data from the switching.

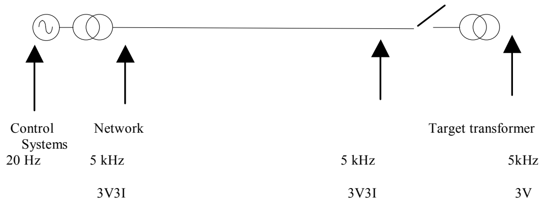


Fig. 6. Location of the measurements during field tests

The measurements allow to get interesting data in order to improve the models adopted for the simulations. The measurements made on the automatic voltage regulator of the generator are useful to check the way the generator voltages are controlled, in case of harmonics; those made on the LV side of the target transformer are necessary for the determination of the remanent fluxes in the transformer; the measurements made on the speed governor are used in the following phase of supplying power to the auxiliaries.

The measurement device is both a recorder and an oscilloscope. The capacity of our equipment allow to record quick phenomenon during a long time. The accuracy of the acquisition devices is better than 1%.

B. Precision on the measurements

The precision on the measurements must be taken into account in the criteria of comparison between simulations and measurements.

The voltages are measured via on site measuring voltage transformers. The error on the voltages are less than 0,5% for the voltages between 0,8 and 1,2 Un. For the higher values, the error can reach 3% for the phase–to-earth voltages, and 6% for the phase-to-phase voltages.

The inrush currents are generally measured with both on site protective and measuring current transformers. The precision depends thus on the tests values reached, compared to the rated values of the current transformers. On measuring transformers for example, the specified precision has not been defined for currents values lower than 10% of the current transformer rated value, which can limit the validity of the comparison with simulations, especially for fitting the damping effects [3].

IV. COMPARISON BETWEEN SIMULATIONS AND MEASUREMENTS

The initial conditions of the tests are evaluated from the measurements. These data are put in our models, always taking into account the dispersion on the network characteristics. Then, a rather good comparison between measurements and simulations allows to validate the re-energization scheme. Furthermore, both models adopted and their data are improved.

A. Initial conditions

The initial conditions are obtained via the analysis of the measurements, i.e. the closing times of the three poles of the circuit breaker that switch on the transformer, and the remanent flux values in the transformer iron core.

- Switching times

First, the switching times are obtained from the measured currents. The delay between the maximum of one phase voltage and the apparition of a disturbance on the currents is measured. This delay between the closing times can reach almost 80 ms, which is the worse case recorded; delays as high as 20 ms are however frequent. The closing times can be obtained from the recordings with an evaluated precision of +/-1 ms; in some cases their evaluation is less precise.

- Remanent fluxes

The remanent fluxes in the core for the three phases of the transformer can be obtained via the integration of the voltages measured on the transformer windings during its disconnection. Voltages are usually recorded on measuring voltage transformers directly connected to the low voltage windings.

The following figure illustrates the calculation of these three fluxes.

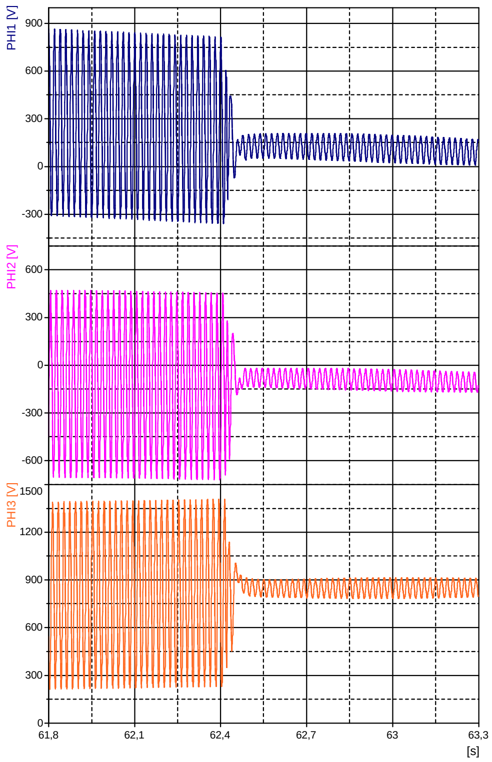


Fig. 7. Computation of the remanent fluxes on the three phases of the transformer

The starting of the integration is determined in order to get steady-state fluxes without any DC component before this disconnection. Nevertheless, we have a superimposed 50 Hz AC component in the measured signal probably due to the capacitance of the circuit breaker. Because of the remanent induced voltages and therefore sinusoidal fluxes after the disconnection of the transformer, we consider that the remanent flux values can't be obtained with a precision better than +/- 10%.

B. Comparison criterion in order to compare simulations to measurements and validate the models

The inrush currents give a lot of informations: the initial conditions (instants of switching on), the peak current values and their attenuation, and help to build the magnetization cycle of the transformer.

The comparison criterion between measurements and simulations data is firstly based on the maxima of inrush currents. A mean square error computation allows to fit the computed values within the uncertainty range adopted. Other type of comparison can also be used, like the comparison of the shapes of both the voltages and currents curves (peak values, attenuation,…) or the comparison of the harmonic rates and attenuation.

C. *Sensitivity analysis*

The analysis presented has been done on the peak values of two of the three currents, reached at the re-energization of the transformer. One simulation parameter is changed at a time in order to have an idea of the sensitivity on the results. We have developed a software based on Matlab, that allows multi parameters analysis and comparison between simulations and measurements. In the following figures, we plot the maximum current on phase 2 (I2max) as a function of the maximum current on the phase 1 (I1max) : both simulation results and measurements are plotted for comparison.

- Influence of the uncertainties taken in the models:

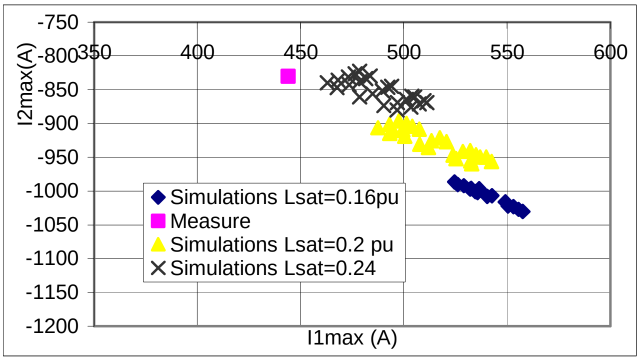


Fig. 8. Influence of the Lsat value on the peak currents computed and compared to the measured currents

The previous figure shows that for a chosen set of initial conditions values, increasing the L_{sat} value within its uncertainty range leads of course to decrease the values of the peak currents. The influence is significant, and it shows that the hypothesis of a minimum value for L_{sat} , made in the study to stay conservative, is not correct.

The influence of the generator reactance (L) and of the over-head line phase-to-earth capacitance (C) values is also taken into account. For one value of L_{sat}, 5x5=25 couples of values (L,C) are simulated. They are displayed on fig. 8. It appears not easy to determine precisely the values of L and C from the simulations, because their influence on the current maxima is low compared to the precision of the measurement transformers. By the means of a Fourier analysis, the uncertainty domain could however be reduced, especially if it is possible during field tests to switch the lines several times.

- Influence of the initial conditions :

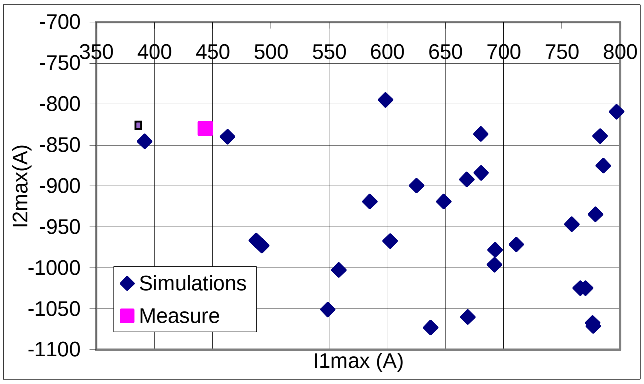
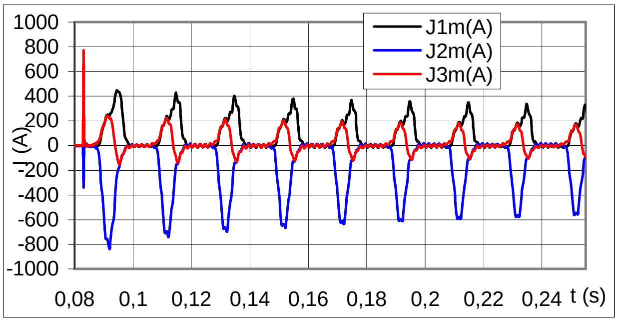


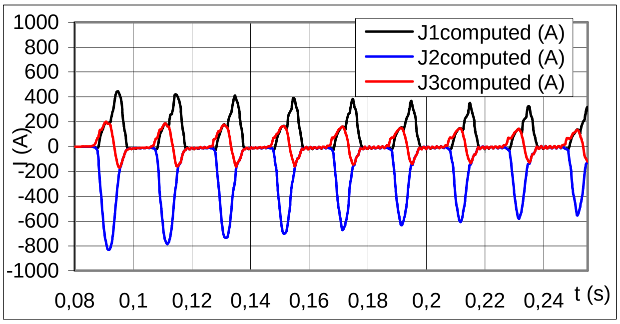
Fig. 10. Influence of the initial conditions on the peak currents computed and compared to the measured currents

Initial conditions, that is to say the remanent fluxes (supposed to be known in a range of +/-10%) and the closing times of the circuit breaker (supposed to be known in a range of +/-1ms), seem to be in that case the most influent factors.

It is therefore possible to adjust and optimize these uncertainties in order to try to fit the current maxima (measurements and simulations). As an illustration, the following figures show, on the currents waves, the comparison between measurements and results of simulation.



Measurements



Simulations

Fig. 11. Comparison between the measured currents and the simulated currents

A rather good agreement is obtained on the comparison of the current shapes and maxima; in the present case, the error on the maxima is less than 5%. Nevertheless, it is not easy to determine an unique combination of parameters, inside the domain defined by the uncertainty values considered.

Some difficulties are also met in representing the current attenuation few periods after the switching of the transformer.

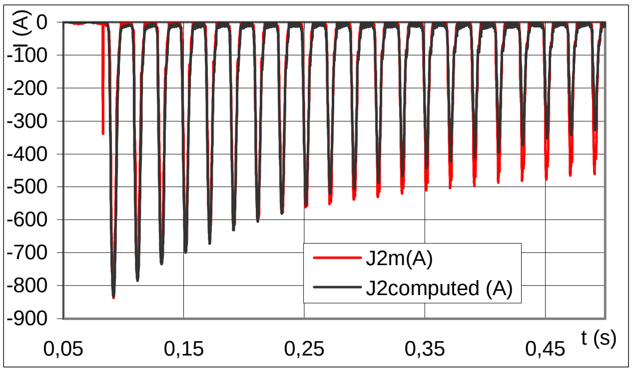


Fig. 12. Comparison between the measured currents with the protective CT (J2m) and the simulated current (J2 computed) for the phase n°2

The results of the simulation are non conservative.

In this type of networks, the attenuation is hard to model because of the low level of the load connected to the network compared to the network losses. Work is still needed for a good modeling of the network losses in the generator, the transformers, the lines [6]. Investigations are currently done with EDF R&D on the models of these elements, by comparison with measurements data. The investigations concern in particular the generator model, in view to analyze the impact of a complete model for in one hand represent better the losses, and in the other hand model the automatic voltage regulator because of the duration of the resonances sometimes reaching several seconds.

V. CONCLUSIONS

This paper was focused on the real case of the re-energization of a large network power transformer, from a power plant located at 50 km. After the study, it was decided to try the field tests, and measurements were performed. The comparison between the measurements and the simulation results, and a sensitivity study, are presented. This paper underlines the need of field tests in order to understand the differences still remaining between measurements and simulations, and to improve the modeling of transient overvoltages with EMTP. Thus, because of the lower damping effect shown by the simulations, it appears necessary to improve the modeling of the losses in the network elements, i.e. the generator, the lines and the transformers, in presence of harmonics.

VI. REFERENCES

[1] Hermann Dommel, “EMTP Theory book”; Hermann Dommel, 1992 edited by Microtran Power System Analysis”, Vancouver, Canada.

[2] J. Mahseredjian, S. Dennetière, L. Dubé, B. Khodabakhchian, L. Gérin-Lajoie, “On a new approach for the simulation of transients in power systems”, IPST 2005, Montréal.

[3] Technical Notice of The EDF Transmission Network Division on the measurement transformers. 1991.

[4] M. Rioual, C. Sicre, “Energization of a no-load transformers for power restoration purposes. Impact of the sensitivity of the parameters”, in Proc. 2001 IPST International Conference on Power Systems Transients, pp 221-227, Rio de Janeiro, Brasil, June 2001.

[5] Sébastien Dennetière, Jean Mahseredjian, Manuel Martinez, Michel Rioual, Alain Xémard, “On the implementation of a hysteretic reactor model in EMTP”, IPST International Conference on Power Systems Transients, New Orleans.

[6] A. Gaudreau, P. Pichet, L. Bolduc, A. Coutu, “No-load losses in transformer under overexitation/inrush-current conditions : Tests and a new model”, IEEE Transactions on Power Delivery, Vol.17, N°4, Oct 2002.

[7] CIGRE WG 33-10, “Temporary overvoltages – Test case results”, Electra n°188, pp70-87, February 2000.

VII. BIOGRAPHIES

François-Xavier ZGAINSKI was born in Oran (Algeria), on may 10, 1970. He graduated from the “Institut National Polytechnique”, Grenoble in 1993, and received a PhD Thesis in electrical engineering in 1996.

His employment experience includes the Cedrat Research Compagny and the French Navy – Grenoble/Toulon (1993-1996), EDF R&D in Paris (1996-2000), and in 2000, he joined the EDF General Technical Department (DTG) in Grenoble. His special fields of interest include modeling and simulation. His main activity deals with transient simulation of temporary overvoltages for network restoration after a black-out and field tests especially in the case of transformers re-energization. He is member of the Society of Electrical and Electronics Engineers in France.

Bruno CAILLAULT was born in Parthenay (France), on april 2, 1961. He graduated from the “Institut National Polytechnique”, Nancy, in 1983, and received a PhD in mechanics engineering in 1987.

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Vincent-Louis RENOUARD was born in Amiens (France), on april 3, 1979. He graduated from the “Institut National Polytechnique”, Nancy, and received a postgraduate diploma in electrical engineering in 2003.

His employment experience includes the Merlin Gerin Electric Uninterruptible Power Supply in Grenoble (2004-2005), and in 2005, he joined the EDF General Technical Department (DTG) in Grenoble. His special fields of interest include modeling, transient simulation of temporary overvoltages for network restoration after a black-out.