Energization of a no-load transformer for power restoration purposes: Impact of the sensitivity to parameters.

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Abstract: **The energization of power transformers following a complete or partial collapse of the system is an important issue. This paper describes a method for the modeling of the electric network between the source and a target transformer, taking into account the data accuracy which has a strong impact on the resonance frequency of the network and consequently on the temporary harmonic overvoltages involved. This methodology has been validated by on site tests, the resonance frequency and the initial conditions being derived from the measurements. Finally a comparison between measurements and EMTP (EPRI/DCG version 3.0) simulations has been performed, showing a good agreement on currents, the average discrepancy being equal to 5 %, the value of the subtransient reactance of the generator and the capacitance of the line having a value within the accuracy initially stated.**

Keywords: Power restoration, transformer energization, modeling, harmonics, temporary overvoltages, ferroresonance.

Nomenclature

$C_{\varphi/t}$:	phase-to-ground capacitance of the overhead lines	(F)
Φ_n :	nominal flux in the target transformer	(Wb)
Φ_{rA} :	residual flux in limb A	(Wb)
Φ_{rB} :	residual flux in limb B	(Wb)
Φ_{rC} :	residual flux in limb C	(Wb)
K_c :	coordination factor taking into account the accuracy of the calculation (IEC 71.1 standard).	
K_s :	aging factor associated to the insulation of the equipment, used in the IEC 71.1 standard.	
$L(\Phi)$:	magnetization inductance including saturation, Φ being the flux in a limb.	(H)
L_{l1} :	leakage inductance of the primary circuit	(H)
L_{l2} :	leakage inductance for the secondary circuit	(H)
L_{sat} :	last slope of the saturation flux-current curve of the target transformer	(H)
R_{Cu1} :	electric resistance of the primary circuit	(Ω)
R_{Cu2} :	electric resistance of the secondary circuit	(Ω)
R_{Fe} :	resistance describing the core losses	(Ω)
S_N :	rated power of the target transformer	(MVA)
U_N :	nominal voltage of the EHV network	(kV)
T''_d :	sub-transient time constant of the generator	(s)
X''_d :	sub-subtransient reactance in the d axis of the generator	(Ω)

1. Introduction

The energization of power transformers, and especially the auxiliary transformers of thermal power plants after a black-out may be an important issue [1].

. It can lead to high overvoltages and currents [2], harmonic phenomena being involved, and also in some cases to ferroresonance conditions [3], [4]. A methodology is described, which takes into account the accuracy of the data for this study, and which may have a strong impact on the resonance frequency of the network.

2. Description of the methodology

In this first part, the methodology is described, including the modeling of the network under harmonic conditions. In those cases related to power system restoration, the electrical network is described by the source generator, the lines and substations between this generator and the target transformer which has to be energized. In the following, a detailed description is performed in the case of a 1300 MW generator, located near Paris in France, the 96 MVA target transformer being energized via a 400 kV double-circuit line having a length of 140 km. This network is shown in figure 1, the circuit-breaker from which the transformer is energized is located in the substation of the thermal plant, 1 km from the transformer:

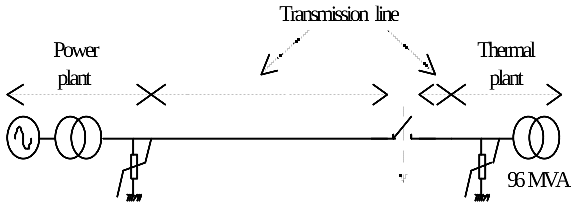


Figure 1 : Description of the 400 kV network.

The power plant includes a 1120 MVA generator followed by a 1080 MVA step-up power transformer. Two zinc-oxide surge arresters, having a rated voltage of 360 kVeff, located at the entrance of the main substations, have been represented.

2.1 Description of the modeling of the network

The equipments of the network have been modeled under the phenomena being involved [7], [10] as follows:

- the 900 MW generator is represented by a sinusoidal voltage source behind its subtransient reactance X''_d and the damping derived from the time constant T''_d, those parameters being given by the manufacturer. However, an accuracy of 15 % is taken on the X''_d value, attributed mostly to the accuracy of the measurements made on it and also to the modeling of this equipment, the other reactances like the transient reactance being neglected.
- the 1080 MVA shell-type step-up transformer is modeled by a three-phase transformer where the leakage reactances, the copper and core losses and the saturation are taken into account. The delta-wye coupling is represented with its grounding reactance of 25 Ω and its dedicated surge arrester. The resistance values are increased in order to take into account the eddy currents and skin effects :

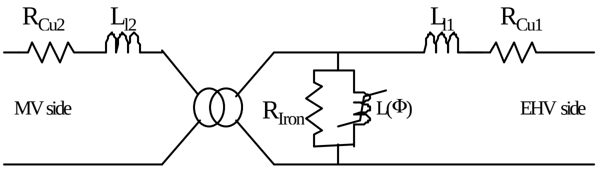


Figure 2 : Description of the transformer diagram (one phase).

Numerical application : R_{Cu1} *= 1.7 W,* R_{Cu2} *= 18.2 mW,* L_{l1} *= 32.1 mH,* L_{l2} *= 0.35 mH and* R_{Iron} *= 0.28 MW.*

- the zinc oxide surge arresters, having a rated voltage of 360 kVeff are represented by their non-linear resistance [8].
- the overhead lines are described by PI cells, the R, L, C parameters being derived from the electrical and geometrical parameters given by the Transportation Division of EDF using an auxiliary routine of the EMTP program. The number of PI cells has been chosen to 10 in order to represent correctly its exact impedance under the fifth harmonic which is the resonance frequency of this network (see figure 3), the skin effect being also calculated at that frequency. Since the sag of the line may vary along its entire length, an accuracy of 5 %, in accordance with the Transportation Division, has been considered for the phase to ground capacitances $C_{\varphi/t}$.
- the corona effect affecting the overhead lines is also represented, by non-linear resistances inserted along the PI cells. Their parameters describing the losses are derived from the ratio between the electrical field generated by the wires and the Peek's critical field.
- the target 96 MVA transformer with its delta-wye coupling is modeled like the previous one [6] except that the hysteretic curve is completely represented. The saturation is built from the voltage-current curve [3] given by the manufacturer. The parameter L_{sat}, describing the slope of this curve under high saturated conditions, is fixed at 0.16 p.u.* that is to say 0.89 H.

Note*: The L_{sat} in p.u. is derived from the one in Henry by the following expression :

$$L_{sat}(pu) = L_{sat}(H)\frac{S_N w}{U_N^2}$$

In fact, the manufacturer has proposed a value of 0.20 p.u. derived from abacus with an accuracy of 20 %, leading to a conservative value of 0.16 p.u.; it takes into account the fact that the value is not completely well defined, the transformer being tested only under low saturation conditions.

A frequency scan has then been performed with the EMTP program on the complete network, as shown below, figure 3 describing the direct impedance; a three-phase current source replaces the saturation part of the target transformer in order to get the equivalent impedance of the network :

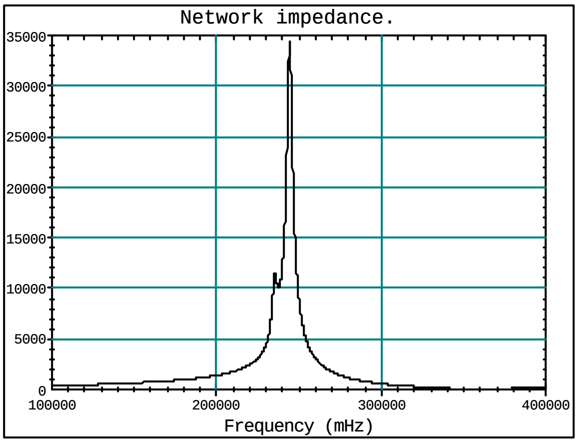


Figure 3 : Direct impedance versus frequency for the 400kV network.

It shows a resonance frequency closed to the fifth harmonic at 244 Hz, the zero impedance being characterized by a frequency at 491 Hz.

Initial conditions, which may have a strong impact on the amplitude of the overvoltages have also been assessed, which is discussed in the following.

2.2 Hypothesis concerning the initial conditions for simulations purposes

The initial conditions concerned when energizing the target transformer are :

- the closing instants of the circuit breaker which operates,
- the residual fluxes circulating in the core of the target transformer before its energization.

In that aim, the following considerations have been taken into account.

2.2.1 Initial conditions associated to the circuit-breaker.

The closing instant of the pole A may occur at any time on the sinusoidal voltage according to a uniform distribution. The two other poles (phases B and C) follow the pole A according to a Gaussian distribution (which is centered on the closing instant of the first pole) characterized by its mean value T_{av} equal to zero and its standard deviation σ which is considered for this breaker to be equal to 20 ms.

2.2.2 Initial conditions associated to the 96 MVA transformer.

We have supposed that the residual fluxes inside the transformer follow a uniform distribution and may reach a value Φ_{max} equal to 80 % of the nominal flux Φ_n (Φ_{max} = 800 Wb), Φ_{max} having a positive or negative value. The sum of these three fluxes vanishes to zero and a symmetry is considered (see table 1). These assumptions are consecutive to the type of the magnetic core (shell-type) and the delta connection at the 6.8 kV secondary side.

Table 1 : Variation of the residual fluxes.

Φ_{rA}	Φ_{rB}	Φ_{rC}
Φ	$-\Phi/2$	$-\Phi/2$
Φ	$-\Phi$	0
$-\Phi/2$	Φ	$-\Phi/2$
0	Φ	$-\Phi$

Φ is the residual flux considered for the simulation; its value varies from $-\Phi_{max}$ to $+\Phi_{max}$ with a step of 400 Wb in this case.

2.3 Calculation of the stresses on the 96 MVA transformer

EMTP simulations have been performed, choosing the parameters X''_d and $C_{\varphi/t}$ which give a resonance frequency very close to an harmonic value, in order to estimate the most severe case.

A scan of the initial conditions with the EMTP program has also been performed (1700 simulations) in order to determine the amplitude of the overvoltages, considering 17 occurences for the residual fluxes and 100 circuit-breaker switchings per occurence.

They reach a value of 1.51 p.u.** (phase to ground), and 1.45 p.u (phase to phase), this last value being the most critical one concerning the stresses on the internal insulation.

Note**:1 p.u. = 342 kV for the phase to ground voltage.

Those values are compared to the withstand voltage of the insulation [9] given by the manufacturer, including the following factors K_s et K_c used in the IEC 71.1 standard in order to assess the integrity of the equipment.

Table 2 : Values of the IEC factors (71.1 standard).

	Phase-to-ground voltage	Phase-to-phase voltage
K_s	1	1
K_c	1.02	1.05

The withstand voltage of the transformer is reached for only one case which represents 0.2 % of the simulations, implying the opportunity to perform on site tests in good conditions. Those tests and the calculation of the initial conditions associated to them are described in the following chapter.

3. Description of the on-site measurements; determination of the initial conditions and the resonance frequency of the network

3.1 On site tests

On site tests have been performed by the Technical Transportation Division of EDF, the 96 MVA transformer being energized from the power plant. An acquisition system has been installed in the substations, especially at the circuit breaker location. Phase-to-ground voltages and inrush currents have been measured from the on site dividers i.e. the voltage and current transformers. All the measurements have been digitized at the sampling rate of 400 Hz, stored and processed using the Matlab software.

3.2 Determination of the initial conditions associated to the on-site tests

They are determined as follows :

- the closing instants of the breaker are obtained from the measurements performed on the inrush currents. For each phase, the closing instant is located (see figure 4 below) when the current of the same pole becomes positive or negative (non zero):

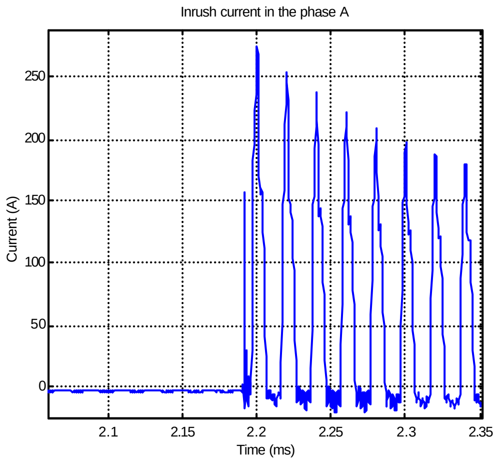


Figure 4 : Inrush current across the 96 MVA transformer (phase A).

In the case of those on-site tests, the closing instants are 2 ms, 7 ms and 7 ms for phase A, B and C respectively. The 0 ms is defined when there is a zero-crossing of the positive wavefront of the phase A-to-ground voltage, introducing a same reference for the measurements and the simulations.

- the residual fluxes can be determined as soon as the target transformer is disconnected before its energization. They are derived from the integration of the phase-to-ground voltages of the transformer (primary side at 400 kV) after the opening of the circuit breaker.

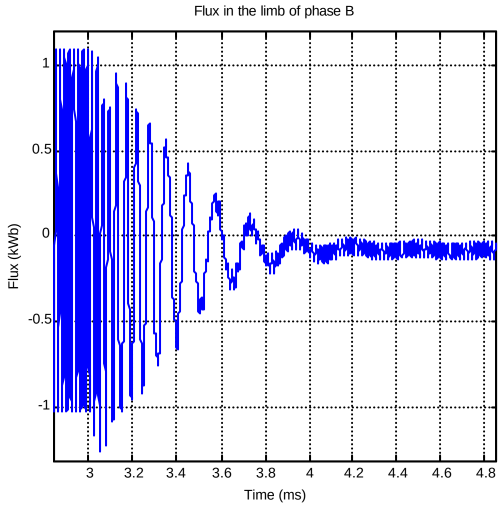


Figure 5 : Evolution of the flux in the limb B when the circuit-breaker opens.

Since the steady-state fluxes have no DC component, the starting time of the phase-to-ground voltage integration is determined in order to compute the simulated fluxes without this component before the disconnection. Nevertheless, a DC noise is present in the measured signal and therefore has been filtered to perform this operation correctly. In that case, the residual fluxes obtained are 0 Wb, -75 Wb and 75 Wb in the limbs of phases A, B and C respectively. That represents about 7 % of the nominal flux of this transformer.

3.3 Determination of the resonance frequency of the network

The resonance frequency of the network has been performed by the mean of a Fourier analysis triggered immediately after the energization and made on the measured phase-to-ground voltages :

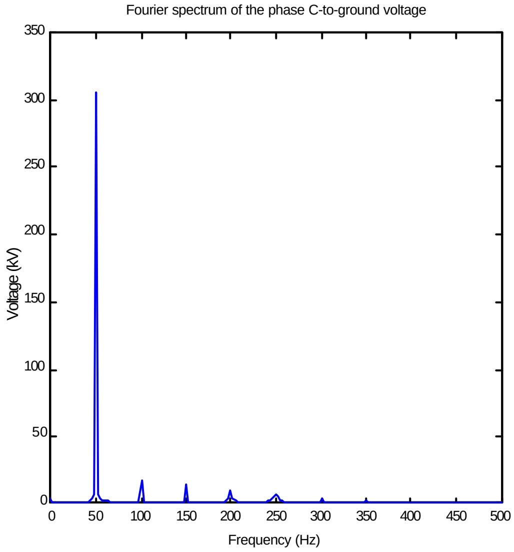


Figure 6 : Fourier analysis of the phase-to-ground voltage on phase C.

When the energization occurs, the magnetic core of the target transformer saturates and therefore highly distorted inrush currents occur, which provide harmonic peaks on the voltage at the transformer entrance. In addition, its spectrum shows another measured peak value centered at 228 Hz (non harmonic), which is consecutive to the excitation of the resonance of this network by those currents when the circuit breaker operates.

By this mean, the resonance frequency for each phase is determined and their values are 240 Hz, 228 Hz and 228 Hz for phase A, B and C respectively.

The average value is 232 Hz, with an accuracy of ±2 Hz due to the accuracy of the acquisition system and especially by the on-site dividers and measuring channels in the substations. The resonance frequency is higher for phase A because the distance between phase A and the ground is more important than for the other phases.

4. Assessment of the network parameters; comparison between on site measurements and simulations

The purpose of this part is to assess the network parameters X''_d, $C_{\varphi/t}$ and also the L_{sat} slope of the saturation curve of the target transformer within their accuracy boundaries and then compare the results between the on-site measurements and the simulations.

4.1 Assessment of the network parameters from the resonance frequency

A frequency scan of the network with its standard parameters gives the resonance frequencies at 244,1 Hz, 235,8 Hz and 238,6 Hz for phases A, B and C respectively, implying an average resonance frequency of 239.5 Hz.
It shows that the discrepancy is 7.5 Hz compared to the measured frequency. Since these parameters X''_d and $C_{\varphi/t}$ are known within an accuracy of 15 % and 5 % respectively, the resonance frequency of the simulated network may reach the measured one when increasing X''_d and $C_{\varphi/t}$ by 11 % and 5 % respectively :

Table 3 : Comparison of the resonance frequency between simulations and measurements.

	Phase A	Phase B	Phase C
Measured	240 Hz	228 Hz	228 Hz
Simulated	235.2 Hz	226.5 Hz	229.2 Hz
Deviation	*2.0 %*	*0.7 %*	*0.5 %*

The average resonance frequency of the simulation is 230.3 Hz. This value is inside the accuracy range of the measured one.

4.2 Determination of the slope L_{sat} of the saturation curve f (i) for the target transformer

During the first times (periods of 50 Hz) immediately after the closing of the breaker, the inrush currents mainly depend on the saturation curve of the target transformer and especially on the L_{sat} slope of this curve. The amplitude of the inrush currents, described in the figure 4, is reached at the first instants.
With a L_{sat} equal to 0.16 p.u. (conservative side), the maximum is reached for the pole A which implies a maximum discrepancy of 21.5 %, the simulations computing 333 A instead of 274 A measured.
If this last value is set to 0.21 p.u. which is in the accuracy boundaries (0.20 p.u. ± 20 %) given by the manufacturer, the discrepancies reach their minimum values i.e. 2.2 %, 13.7 % and 4.4 % for the phases A, B and C respectively.
This comparison sets the value of L_{sat} of the transformer which is very closed (less than 5 %) from the average value given by the manufacturer in that case.

4.3 Calculation of the losses in the network

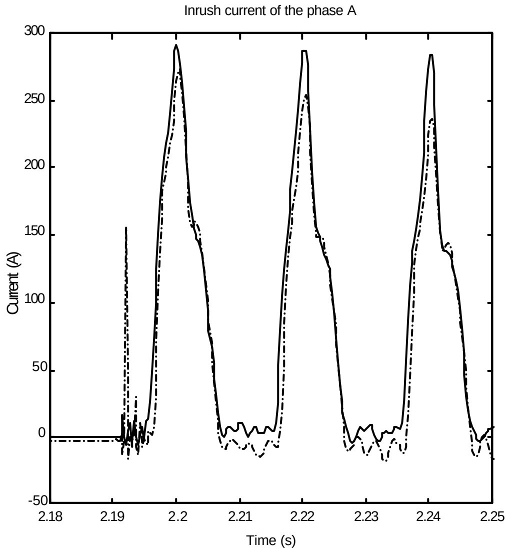
The influence of the losses in the network (due to corona, skin effects, and eddy currents) on the damping of the inrush currents is an important parameter. In this part, the resistances modeling the losses (see figure 2) are computed in the way to take into account the harmonic average distribution of these currents corresponding to 88 % of 50 Hz and 12 % of 250 Hz in that case, leading to the following table for the inrush currents calculated by EMTP:

Table 4 : inrush currents: comparison between simulations and measurements, taking into account the real harmonic distribution (L_{sat} equal to 0.21 p.u.).

	Phase A	Phase B	Phase C
Measured	274 A	161 A	342 A
Simulated	292 A	147 A	342 A
Deviation	*6.6 %*	*8.7 %*	*0 %*

This average discrepancy is 5 %; for longer times e.g. 400 ms, it reaches 10% on phase C and 14% and 19% for phase A and B.

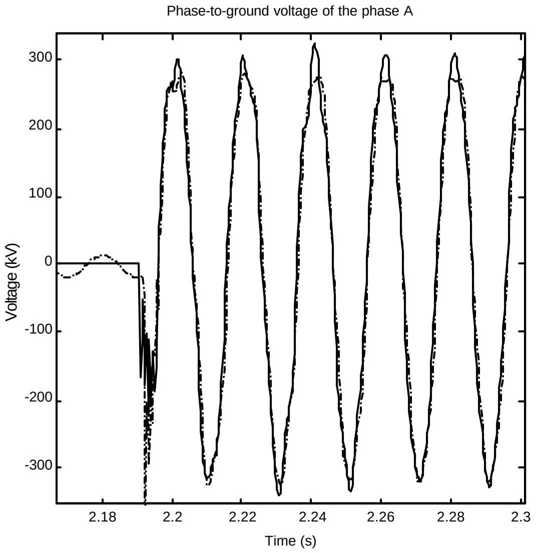
Figure 8 shows the simulated and the measured inrush current of the phase A :



--- (dotted line): field measurements
__ (straight line): simulations

Figure 7 : Inrush current of the transformer during the first instants.

The phase-to-ground voltage of the phase A is described as below:



--- (dotted line): field measurements
__ (straight line): simulations

Figure 8 : Phase-to-ground voltage during the first instants.

There is also a good agreement between simulations and measurements.

5. Conclusion

This paper describes a method for the modeling of the energization of power transformers taking into account the data accuracy (line capacitances, subtransient reactance of the generator, air core reactance of the target transformer) which has a strong impact on the resonance frequency of the network and also on the temporary harmonic overvoltages and currents involved. Those parameters have been assessed inside their accuracy boundaries from on site measurements on a real network. After the determination of the resonance frequency and the initial conditions, a comparison between measurements and EMTP simulations has been performed, showing a good agreement on inrush currents and overvoltages, the average discrepancy being equal to 5%.

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