Simulation of the effect of parameter uncertainties on transient overvoltages during power restoration: comparison with field measurements

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***Abstract*—In case of an electrical blackout, it is essential to restore the network as safe and fast as possible. To do so, available power generating units have to energize the nearest ones, which in turns, will be able to energize the whole network. This implies to power up overhead lines, transformers, shunt reactances and underground cables. Wherever possible, generating units which have black start capability are used. This enables to gradually increase the voltage in order to minimize the risk of overvoltage. In this paper, a detailed modelling of such a scenario is presented. As it is well known that the results of such studies are extremely dependent on the initial conditions and on data input which are known with a certain degree of accuracy, many simulations have to be performed to obtain robust statistical results. To cope with all these uncertainties and constraints, PAMSuite, a software program developed at EDF, aiming at performing parametric and probabilistic studies with EMTP-RV, has been used. A few tens of thousands of EMTP simulations have been launched to explain the phenomenon by an extended comparison between measurements and simulation results and to precisely estimate the risk of damaging electrical components. Different voltage setpoints of the power source have been considered in the simulations to minimize the risk of overvoltage as much as possible.**

***Keywords*: Voltage restoration, comparison between measurements and simulations, residual flux, ferroresonance, transformer saturation, inrush currents, EMTP-RV, PAMSuite**

I. Introduction

When energized, a transformer is likely to temporarily absorb a significant amount of reactive currents. Depending on the surrounding network, these inrush currents can go together with significant overvoltage: this specific type of resonance caused by the non-linear inductance of the transformer and the capacitance of the network is known as ferroresonance [2], [9]. Although this is a well-known phenomenon, it is still feared when performing voltage restoration. This is due to the fact that the results of these tests are extremely variable and dependent on the initial conditions - most of them are unknown - and on the variability of parameters that are known with a certain degree of accuracy.

To minimize the risk of overvoltage, generating units which have black start capability are used whenever it is possible. This enables the voltage to be gradually increased, typically from 0 to 90% of the nominal voltage in 10 to 30 seconds. When such a scenario is not possible, the energization is carried out by closing the transformer circuit breaker on a network which voltage level is imposed by the islanded unit: this is called a sudden voltage restoration. These types of cases are particularly taken care of [7], [8]. The methodology used in such studies is described in [2].

Although they are less studied, gradual voltage restorations can also present overvoltage risks as it has been explained in the literature [6]. This will be covered in details in this paper.

Section II will present the study case and the study methodology. Section III will cover the modelling of each electrical component. Section IV will present the assumptions used for the statistical study. Section V will focus on a specific simulations whose results are close to the measurements. Section VI will present the results of the voltage restoration study while Section VII will analyze the effectiveness of several mitigation measures.

II. Study Case

A. Field test system

The simplified electrical schematics is shown on Fig. 1. The two points at which voltage and current have been measured during the on-site tests are shown with green arrows.

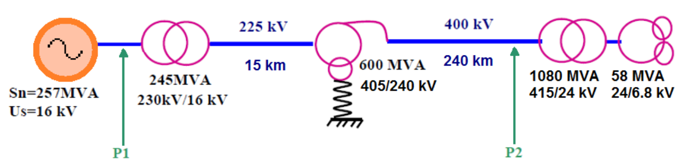

Fig. 1 Simplified electrical schematics of the voltage restoration

This case is particularly complex due to two factors. First, four transformers are gradually energized at once, with a high total rated power compared to the one of the power unit. Second, the total overhead line length is rather long for performing a voltage restoration: about 250 km.

During the voltage restoration field test performed in 2015, some unexpected overvoltages have been measured along the line although the voltage setpoint of the 257 MVA power generator voltage regulator has been increased gradually (from 0 to 90% of the generator rated voltage in 28 seconds).

B. Study methodology

The study has been performed in 3 stages, all by computer simulation with EMTP-RV:

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- Understand what happened during the field test by finding a simulation case whose results are close to the measurements. This will enable to observe physical values that have not been measured during the real test;
- Evaluate the probability of damaging the transformers for other initial conditions than those of the 2015 field test and considering uncertain parameter values, due to the differences still remaining between measurements and simulations;
- Evaluate the performance of possible mitigations measures aiming at decreasing the probability of damage.

III. Modelling

A. Power plant

The power plant consists of a 50 Hz / 257 MVA / 16 kV / 2 poles power generator with a static excitation system. It has been modeled using Park equations. Some of the required values were not available (X'q, T'q and T''q). As it has been checked that they do not have a significant influence on the results, they have been assigned typical values.

TABLE I
Values of the Park model of the power source generator

f_N	Nominal frequency	50	Hz
N_P	Number of poles	2	
V_N	Nominal voltage	16	kV
S_N	Nominal power	257	MVA
i_{agl}	Rotor current at nominal stator voltage	723	A
Ra	Stator resistance	0.0015	pu
X_0	Zero-sequence reactance	0.10	pu
X_l	Stator leakage reactance	0.175	pu
X_d	d-axis synchronous reactance	1.91	pu
X_q	q-axis synchronous reactance	1.84	pu
X'_d	d-axis transient reactance	0.30	pu
X''_d	d-axis subtransient reactance	0.22	pu
T'_d	d-axis short-circuit (s.-c.) transient time constant	0.9	s
T''_d	d-axis s.-c. subtransient time constant	0.05	s
X'_q	q-axis transient reactance	0.55	pu
X''_q	q-axis subtransient reactance	0.35	pu
T'_q	q-axis s.-c. transient time constant	0.2	s
T''_q	q-axis s.-c. subtransient time constant	0.05	s

The saturation of the machine has also been represented as its open-circuit curve was available:

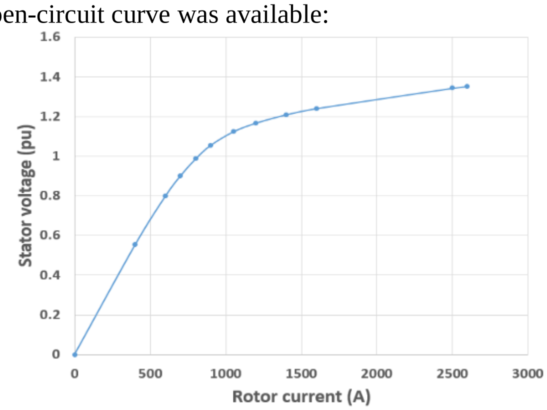

Fig. 2 Open-circuit curve of the power generator

The automatic voltage regulator of the generator (AVR) has also been modelled in EMTP. It consists of a PI controller with a voltage stabilization loop:

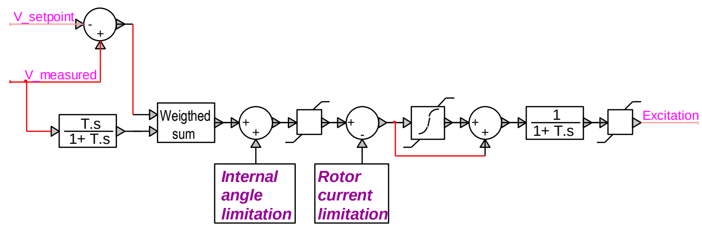

Fig. 3 Simplified voltage regulation schematics

As a reminder, the voltage setpoint is a ramp which goes from 0 to 90% of the generator rated voltage in 28 seconds. The measurement system of the stator voltage has also been modeled.

B. 2-Winding transformers

2-Winding transformers have been modelled using the nonlinear version of the classic Steinmetz model [5]:

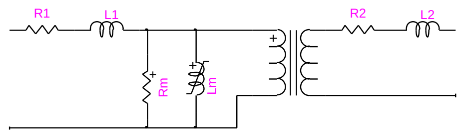

Fig. 4 Model of the transformer (one phase shown)

The values of the 245 and 1080 MVA transformers are shown on Table II.

TABLE II
Values for the 245 and 1080 MVA transformers

S_N	Nominal power	245	MVA	3*360	MVA
f_N	Nominal frequency	50	Hz	50	Hz
U_1	HV Voltage	230	kV	415	kV
U_2	MV Voltage	16	kV	24	kV
X_{sc}	Short-circuit impedance	12.8	%	14.14	%
P_C	Copper losses	603	kW	3*738	kW
P_I	Iron losses at U_N	113	kW	3*144	kW

Their magnetization inductances L_m have been calculated using the open-circuit test. They have been carried out up to 120% of the rated voltage for the 245 MVA transformer and up to 113% for the 360 MVA transformer. The last point is extrapolated using the value of the saturation inductance. To be calculated, this value requires the air-core inductance (the inductance of the windings without the core) which represents the behavior of the transformer when its core is fully saturated. This will be further explained in part IV.

C. Autotransformer

It is a 50 Hz / 600 MVA Yy0d11 autotransformer. Its tertiary winding is connected to a 6.8 Ohms reactance, aiming at compensating the capacitive behavior of the unloaded line.

Again, the transformer has been modeled using the nonlinear version of the classic Steinmetz model. Its main characteristics are given on Table III.

Its magnetization inductance has been calculated using the open-circuit test which has been carried out up to 110% of the nominal voltage. Beyond, it has been extrapolated using the value of the air-core inductance of 0.7 H (0.8 pu) which has been given by the manufacturer.

TABLE III
Values for the 600 MVA autotransformer

S_N	Nominal power	600	MVA
f_N	Nominal frequency	50	Hz

U_1	HV1 Voltage (Y)	405	kV
U_2	HV2 Voltage (Y)	240	kV
U_3	MV Voltage (d)	21	kV
$u_{sc-HV1-HV2}$	Short circuit impedance between HV1 & HV2	14.2	%
$u_{sc-HV1-MV}$	Short circuit impedance between HV1 & MV	65.4	%
$u_{sc-HV2-MV}$	Short circuit impedance between HV2 & MV	43.5	%
$P_{C-HV1-HV2}$	Copper losses with HV1 & HV2 energized	1200	kW
$P_{C-HV1-MV}$	Copper losses with HV1 & MV energized	80	kW
P_I	Iron losses at U_N	137.3	kW

D. 58 MVA transformer

It is a Yd11d11 58 MVA 24/6.8 kV transformer. Its open-circuit tests were carried out up to 105 % of the nominal voltage.

E. Overhead lines

Each part of the restoration line has been modeled by eight coupled Pi sections [4], as only their zero and positive sequences were known. It was not possible to obtain the geometrical characteristics of the towers within the timescale of the study.

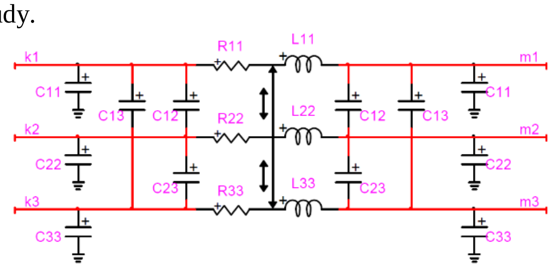

Fig. 5 Coupled Pi section for a three phase line

The biggest section is a bit less than 100 km, which is around the maximum length which can be represented by a Pi circuit for such studies, where the frequencies of inrush currents are negligible beyond 1 kHz [2]. Using frequency dependent models for the overhead lines is likely to be addressed in a future work.

IV. Probabilistic Study Assumptions

As it has already been explained, the results of this kind of study are highly dependent on the initial conditions and on input data which are known with a certain degree of accuracy. This is the reason why a probabilistic study had to be carried out.

To do so, PAMSuite, a software program recently developed at EDF R&D [10], [11], aiming at performing parametric and probabilistic studies with EMTP-RV, has been used. This software program uses Monte-Carlo theory to launch several EMTP models and gets the results back to compute all the outputs needed by the user in terms of probability calculation.

The following uncertain parameters have been considered:

- Parameters of the power generator. According to the standards [1], it has been assumed that all parameters can vary from -15% to +15%. A uniform density probability has been used;
- The initial states of magnetization of the transformers. According to [2], it has been assumed that the amplitude of the initial magnetization could be up to 80% of the nominal value: a uniform density probability has been used. Logically, the value on each phase is 120° phase-shifted;
- Values of the air-core inductance.

For the case when the value has been given by the manufacturer, a typical uncertainty of ±20% (as specified by manufacturers) has been added through a uniform law;

For the case when this data was not available, a probability density which takes into account all the possible cases had to be chosen. For large power transformers, this value is most of the time comprised between 0.2 and 0.9 pu with the most likely value being around 0.3 pu [2]. This is the reason why the following triangular function has been used for the probability density of this parameter:

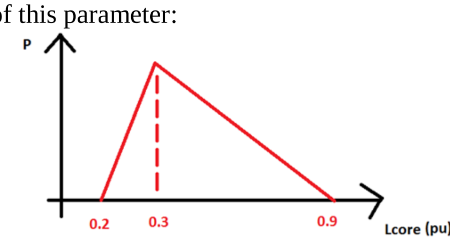

Fig. 6 Probability density of the air-core inductance

Then the saturation inductance can be calculated with the following formula:

$$L_{sat} = L_{air-core} - k \cdot L_{sc} \qquad (1)$$

where L_{sc} is the short circuit inductance and k is a factor representing how the total leakage inductance is split between both sides of the ideal transformer unit ('L1' and 'L2' on Fig. 4). It is assumed here to be 0.5. The L_{sat} value is the last slope of the magnetizing curve of the non-linear inductance L_m.

The magnetizing inductance curves for the 245 MVA Generator Step-Up (GSU) transformer are shown on Fig. 7 for the extreme values of $L_{air-core}$. The first four points are calculated from the measurements and the last point is approximated as explained above. Note that the saturation is represented at the 230 kV (HV) side.

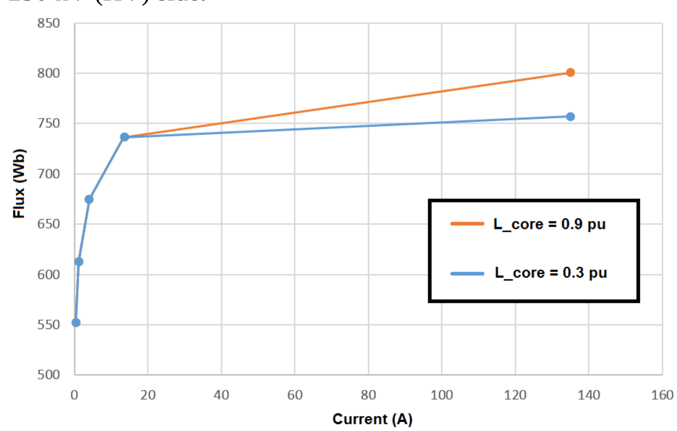

Fig. 7 Magnetizing curve of the 245 MVA GSU Transformer

- Capacitance values of the overhead lines: they have been assumed to have a ±10% uncertainty.

Given all these assumptions, a few hundreds of simulations have been launched. As the software program enables to run simulations in parallel (as many parallel tasks as there are cores on the processor), it took only a few hours to have 2500 simulations completed.

First, a simulation whose results are close to the test measurements will be shown.

V. Simulation close to the test measurements

The simulation considered is the one of the 2500 simulations which minimizes the difference with the measurements at the 400 kV side (voltage and current on phase A). The associated curves are shown on Fig. 8 to 13. There are still significant differences between the simulations and the measurements: the overvoltages are smaller in the simulation than in the real case. Still, it is very useful to compare them so as to understand the physical phenomenon leading to the overvoltage before carrying a more general study. This will also enable to observe physical values that have not been measured during the real test.

In the simulations and the measurements, the voltage ramp is easily followed by the generator: it goes from almost 0 to 90 % of the generator rated voltage in 28 seconds:

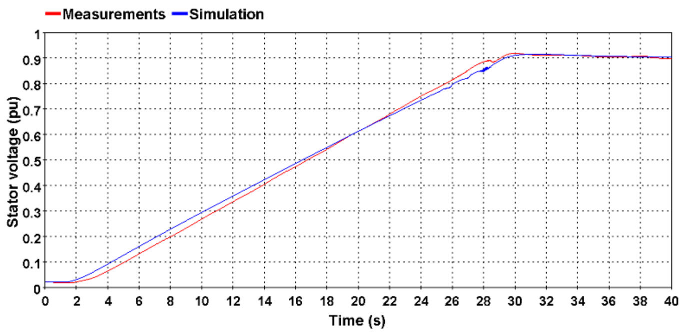

Fig. 8 Stator Voltage (16 kV side)

There are no abnormal phenomena before 20 s in both simulations and measurements. After that, some overvoltages appear. The peak-envelope of voltage and current at the 400 kV side (measurement point P2 on Fig. 1) are shown for phase A:

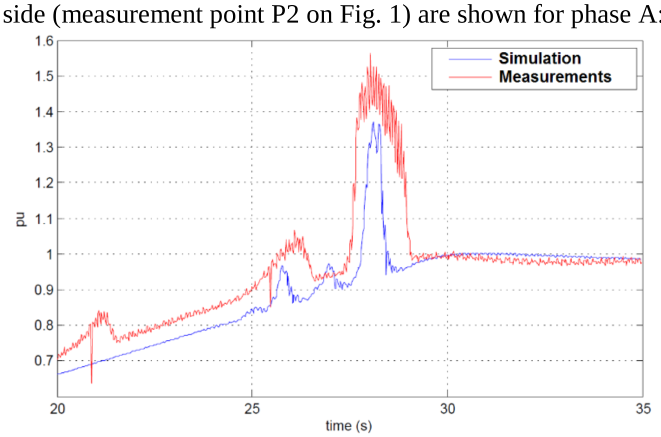

Fig. 9 Voltage at 400 kV side (base 420 kV)

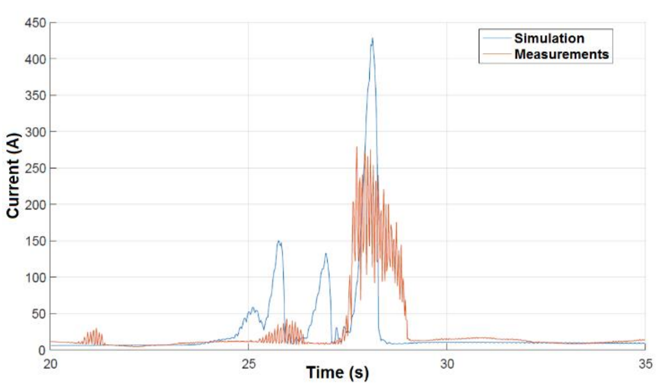

Fig. 10 Current at 400 kV side

In the simulation, the reactive currents absorbed by the transformers have a higher peak but last for a smaller time than in the measurements. This leads to simulated overvoltages which are smaller than the measured ones.

The simulation also enables to observe the flux and magnetizing currents of the transformers along the restoration line (Fig. 11). Their values are coherent with the magnetizing inductances that have been inputted. The initial value of their flux is different from 0 because of the residual magnetization. Even if the voltage is gradually increased, it takes time for the transformers to reach the steady-state magnetization flux: after 40 seconds of simulation, only the 1080 MVA transformer is almost "demagnetized" from its initial residual flux (the peak flux are almost the same on its 3 phases).

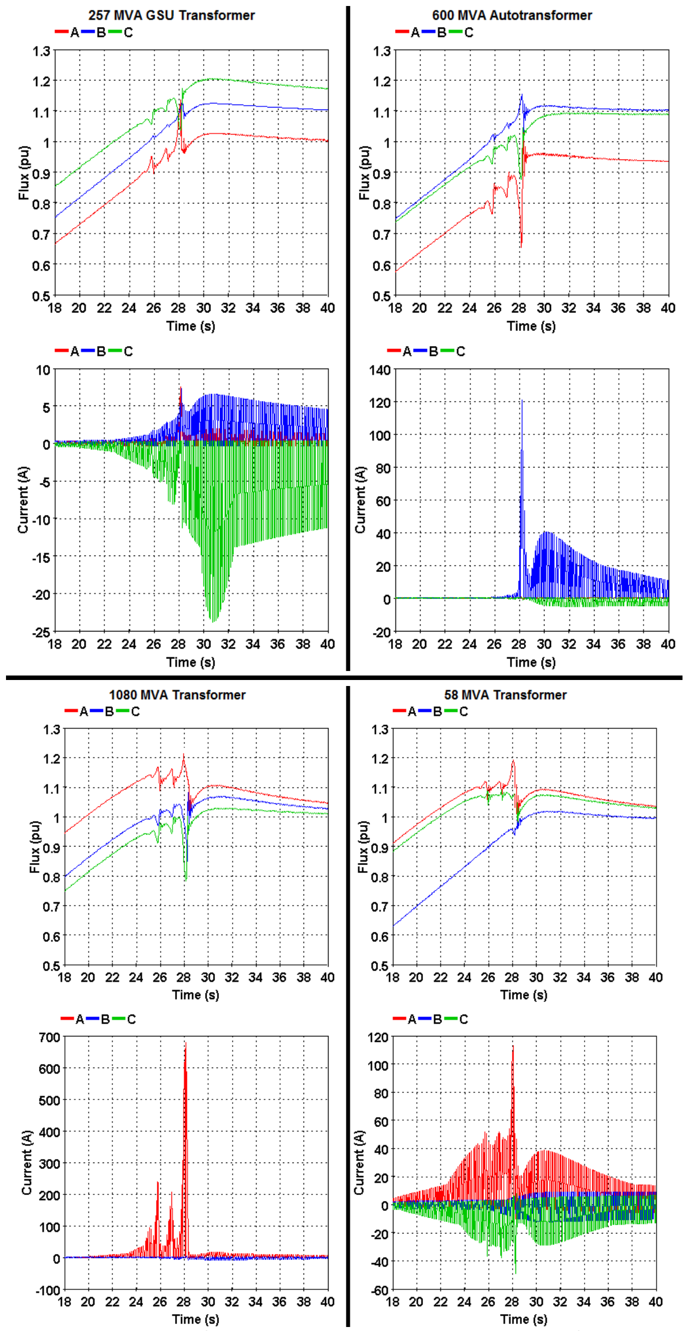

Fig. 11 Simulated flux (peak value) and magnetizing currents for the 4 transformers from t = 18 to 40 seconds

As the transformers are transiently absorbing significant amounts of inrush currents which are by nature reactive, the reactive power which is absorbed by the generator is decreasing quite rapidly in both simulations and measurements (visible at t=28s on Fig. 12).

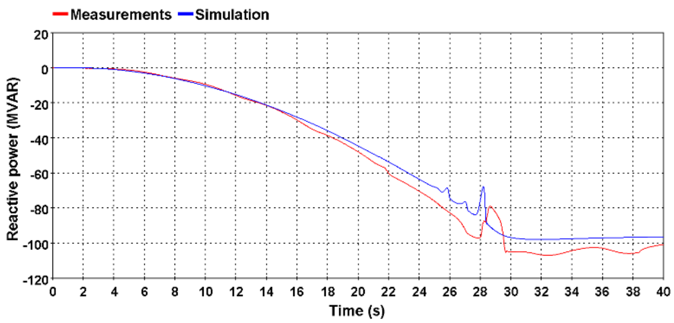

Fig. 12 Reactive power flowing from the 225 kV side (P1)

This can also be seen when looking at the rotor current of the power generator source which shows a high peak at the same time:

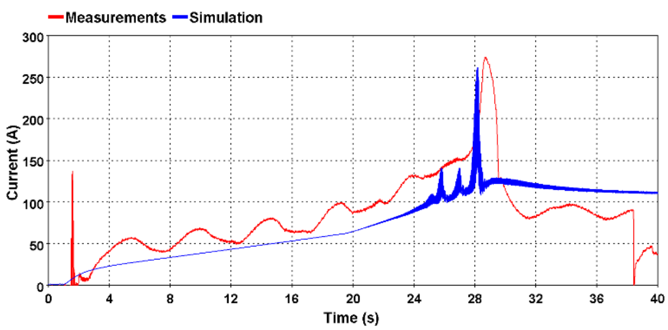

Fig. 13 Rotor current of the power generator

VI. General Voltage Restoration Study

The aim of this part is to assess the probability of damaging the 1080 MVA transformer for any possible value of the uncertain parameters. To do so, the 3 phase-to-ground voltages at the transformer line terminals will be considered. To be sure not to damage it, two criterion used at EDF will be used:

- The voltage cannot exceed 1.63 pu for more than 1 s (criteria 1);
- The voltage cannot exceed 1.72 pu for more than 100 ms (criteria 2).

These criterion take into account the failure of one of the surge arresters, which is also an unwanted event.

Based on the 2500 simulation samples, the probability of damaging the transformer or failing one of its surge arresters is estimated to 49% (with a ±2% confidence interval for 95% confidence). This is very likely to be significantly overestimated. This overestimation can be explained by the following aspects:

- As the open-circuit curve is always quite incomplete (because the open-circuit tests are carried out until 120% of the nominal voltage in the best cases), the magnetizing inductance is quite approximate for high values of saturation (cf. Fig. 7). The knee of the curve is indeed very difficult to calculate. The current model is clearly overestimating the way the transformer is saturating.
- The more losses there are in the network, the quicker the transformer will demagnetize. In the modeling, some losses are underestimated, especially because the dependency of the losses over frequency (for the transformers and the overhead lines) is not considered. This explains why the inrush currents of the transformers are overestimated as well as the resulting overvoltage.

With this modeling, some cases can lead to ferroresonance, with overvoltages sometimes reaching 3 pu (with 1 pu = 420kV). This can be seen on Fig. 14 where the 400 kV voltages of the 100 worst cases (i.e. which show the biggest values and durations of overvoltage) are plotted:

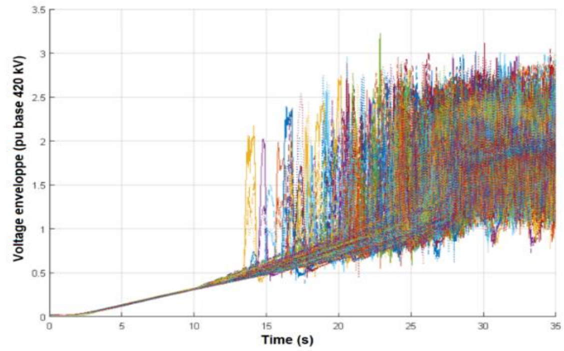

Fig. 14 Voltage envelope of the 100 worst cases

VII. Evaluation of Mitigation Techniques

There exist devices that are able to demagnetize power transformers [3]. However it is not realistic to use them in the case of a voltage restoration. Consequently, the only solution is to change the voltage setpoint of the power generator. Different alternatives have been tested by simulation:

- Raise the voltage up to 80% in 30 s
- Raise the voltage up to 80% in 50 s
- Raise the voltage up to 80% through different stages

At the end of the automatic increase of the voltage, an operator slowly increases the voltage of the generator step by step using small increments (typically around 1% of the nominal voltage) up to the satisfactory value for the proper functioning of the energized power plant. This is why raising initially the voltage up to 80% instead of 90% is not problematic.

A. *Raise the voltage to 80% in 30 s*

The study has shown that this option can dramatically decrease the risk of damaging the transformer: the probability is now 14.5% (±1.5%) with this new setpoint. The number of problematic cases is considerably reduced as it can be seen on Fig. 15 when looking at the 100 worst cases:

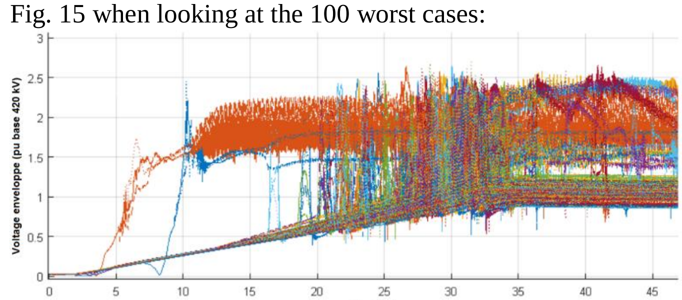

Fig. 15 Voltage envelope of the 100 worst cases for 80% in 30 s

B. Raise the voltage up to 80% in 50 s

As it could be coherently expected, raising the voltage more gradually also reduces the number of problematic cases as it gives more time to the transformers initial fluxes to decrease. The probability decreases to 7% (±1%). This is an encouraging result as it has already been explained that the risk is overestimated.

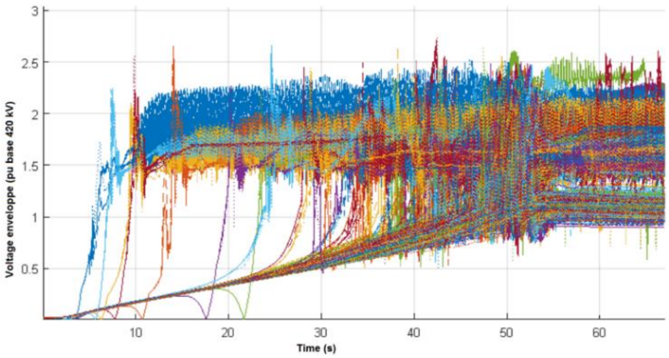

Fig. 16 Voltage envelope of the 100 worst cases for 80% in 50 s

It is interesting to note from Fig. 16 that there are still some problematic cases where overvoltages occur even at the early stages of the power source voltage increase.

C. Raise the voltage up to 80% through different stages

The voltage setpoint of Fig. 17 has been considered. It is important to note that it has not been checked yet if this is technically implementable on site.

Fig. 17 Voltage setpoint raising up to 80% through different stages

With this voltage setpoint raising, the probability decreases to 6% (±1%). This is not a significant gain compared to the previous uniform setpoint raising.

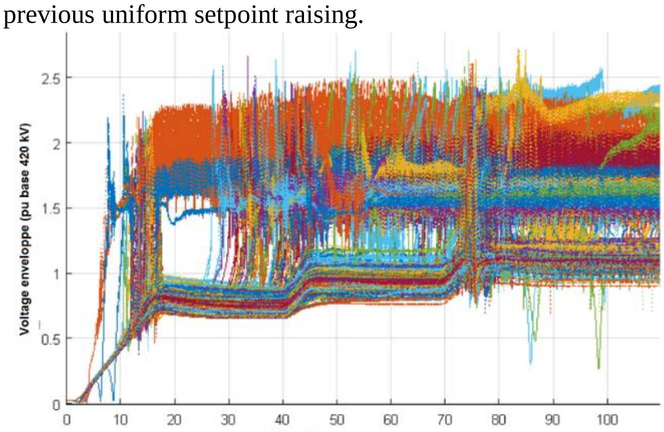

Fig. 18 Voltage of the 100 worst cases for 80% through different stages

VIII. Conclusion

A time-domain modeling of a gradual voltage restoration has been carried out with EMTP-RV. Using PAMSuite, a software program recently developed at EDF R&D for performing EMTP studies with parameter uncertainties, it has been possible to:

- Explain what happened during the field test;
- Quantify the risk of damaging transformers or failing one of its surge arresters in other field tests;
- Evaluate the effectiveness of several mitigating measures.

It is planned to decrease the final value at 80% instead of 90% of the rated voltage. The raise time will be increased in order to avoid the saturation of the transformers. These modifications are likely to be implemented in the next years before a final test that has to be done in 5 years.

Despite these interesting results, future work is necessary to:

- Check if the AVR can be modified and if the modification of the energization sequence is accepted by the Transmission System Operator;
- Better estimate the risk of damage by a better modelling of power transformers and overhead lines.

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