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Simulation of a gradual power restoration: Effect of parameter uncertainties on transient overvoltages and comparison with field measurements

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ABSTRACT

In case of an electrical blackout, it is essential for Transmission System Operators and Electric Utilities to be able to restore the network as 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, reactances and underground cables.

A transformer which is energized is likely to temporarily absorb a significant amount of reactive currents. Depending on the surrounding network, these 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.

Depending on the power source, the voltage restoration can be of two types:

- sudden, which means that the energization is carried out by closing the transformer circuit breaker on a network which voltage level is imposed by the islanded unit;
- or gradual, which means that the voltage of the power source is gradually increased. This is possible when the generating unit has black start capability.

This last type is considered less critical as it gives more time for the transformers to have their flux DC component back to zero.

To be prepared to such events, voltage restoration scenarios are regularly tested. During one of these tests that will be fully presented in the paper, measurements carried out at several points along the energized network have shown significant inrush currents and overvoltages. Although the voltage source was gradually increased, the transformers residual fluxes did not have enough time to fully decay, this is the reason why some of the transformers had saturated.

To understand what happened and quantify the risk of occurrence, the entire case has been modeled on EMTP-RV. The complexity of such a case can be explained by several factors:

- Four transformers are energized at once. Their initial states of magnetization are unknown and independent from each other, as well as their magnetization characteristics;
- The overhead lines are long and their electrical characteristics are known with a certain degree of accuracy;
- As the voltage increase has to be simulated entirely in time-domain, the automatic voltage regulator and the generator of the power source have to be modeled precisely;
- As it is well known that the results of such studies are extremely variable and dependent on the initial conditions, many simulations have to be performed to obtain robust results.

To cope with all these uncertainties and constraints, a software 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:

- First to understand and explain the phenomenon (by an extended comparison between measurements and simulation results);
- Then to precisely estimate the risk of damaging electrical components.

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Different voltage setpoints of the power source have been considered in the simulations to minimize the risk of damage as much as possible.

1. 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 [1,2]. 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 10–30 s. 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 have been particularly analyzed and discussed [3,4]. The methodology used in such studies is described in Ref. [1].

Although they are less studied, gradual voltage restorations can also present overvoltage risks as it has been explained in the literature [5]. This will be covered in details in this paper. Indeed, this work has been initiated because of unusual overvoltage and inrush currents that have been measured during a gradual voltage restoration test.

Section 2 will present the study case and the study methodology. Section 3 will cover the modeling of each electrical component. Section 4 will present the assumptions used for the statistical study. Section 5 will focus on a specific simulation case whose results are close to the measurements. Section 6 will present the results of the voltage restoration study while Section 7 will analyze the effectiveness of several mitigation measures.

2. Study case

2.1. 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.

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 s).

2.2. Study methodology

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

- 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.

3. Modeling

3.1. 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 1).

The saturation of the machine has also been represented as its open-circuit curve was available (Fig. 2).

The automatic voltage regulator of the generator (AVR) has also been modeled in EMTP. It consists of a PI controller with a voltage stabilization loop (Fig. 3).

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

3.2. 2-Winding transformers

2-Winding transformers have been modeled using the nonlinear version of the classic Steinmetz model (Fig. 4) [6].

The values of the 245 and 1080 MVA transformers are shown on Table 2.

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

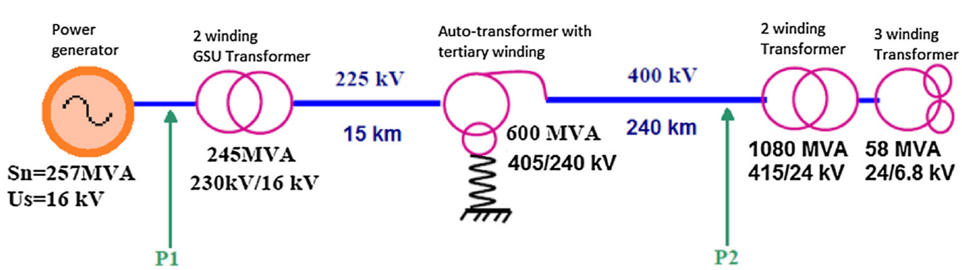

Fig. 1. Simplified electrical schematics of the voltage restoration.