

# ATP/EMTP Study of Ferroresonance Involving HV Inductive VT and Circuit Breaker Capacitance

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**Summary:** Ferroresonance is a phenomenon usually initiated by transients in power networks resulting from e.g. switching operations or ground faults. Non linear behavior of the core of an inductive voltage transformer results in magnetic saturation. Long-lasting ferroresonant state is dangerous to the equipment due to prolonged overvoltage and large overcurrents in HV windings.

In the present article numerical simulations of the ferroresonance phenomenon in a HV inductive VT are presented. The ferroresonant oscillations analyzed result from interaction between the voltage transformer and a grading capacitance of a circuit breaker.

**Key words:**  
inductive voltage transformer, transformer core, ferroresonance, ATP/EMTP, simulation

## 1. INTRODUCTION

Magnetic saturation results in that an inductive component becomes non-linear. The principle of design of magnetic circuits of electrical apparatus and machinery operating in power networks is therefore to ensure that the magnetic flux density does not exceed the saturation level characteristic for the given material used. This criterion has to be fulfilled for normal operating conditions for a given device. It is however, common that the magnetic cores are temporarily subjected to saturation during transient network phenomena such as energizing process of a power transformer, for example. The presence of the non-linear inductance in combination with capacitance in the electrical circuits results in the hazard of the well known ferroresonance phenomenon. The ferroresonant phenomena pose risks to the electrical power networks as magnitude of voltages and/or currents may significantly exceed the maximum allowable values for a given piece of equipment.

Vast literature exist describing the problem of ferroresonance phenomenon in power networks (e.g. [2–4]) as well as solutions aiming at mitigating it (e.g. [4]). A comprehensive summary of the ferroresonance problem was also presented in [5–6].

The ferroresonance is a non-linear resonance phenomenon that can affect power networks. The abnormal rates of harmonics and transient or steady state overvoltages and overcurrents that it causes are often dangerous for electrical equipment. Some unexplained breakdowns can be ascribed to this non-linear phenomenon.

The ferroresonance phenomenon may take place in the case when the core of an inductive device becomes saturated, and its current-flux characteristic becomes non-linear. While in the case of the linear resonant circuit the resonant frequency is well defined, in the case of the non-linear circuit the oscillations may exist at various frequencies, depending on many factors characterizing the particular case.

In practice the ferroresonant oscillations may be initiated by momentary saturation the core of the inductive element resulting from e.g. switching operation or other type of event resulting in a transient overvoltage in the system.

The undamped ferroresonant oscillations in power system are dangerous to the equipment installed due to large overcurrents and/or overvoltages which may ultimately lead to permanent equipment damage.

In the paper numerical simulations of the ferroresonance phenomenon in the HV inductive voltage transformer are presented. The ferroresonant oscillations analyzed result from interaction between the voltage transformer and a grading capacitance of a circuit breaker.

## 2. CASE STUDY: INDUCTIVE HV VOLTAGE TRANSFORMER

Voltage transformers are characterized by a special construction and their rated power is typically very low due to their metrological, rather than power supply function. Nominal primary currents in the voltage transformer VT winding are typically of the order of single milliamps at primary voltage ranging from several up to tens of kilovolts (MV) or hundreds kV (HV).

In order to create an electrical simulation model of the VT, a magnetizing characteristic was measured for the real core of the instrument transformer using test windings. Instantaneous current and voltage values were measured using a digital oscilloscope. Then the voltage values were re-calculated for real numbers of turns. Due to the negligible

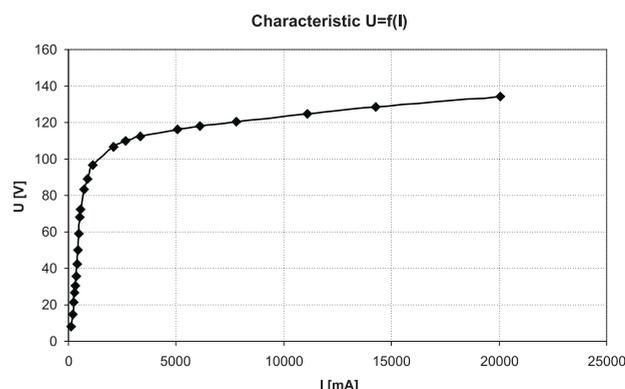


Fig. 1. Measured  $U-I$  characteristic for the voltage transformer core

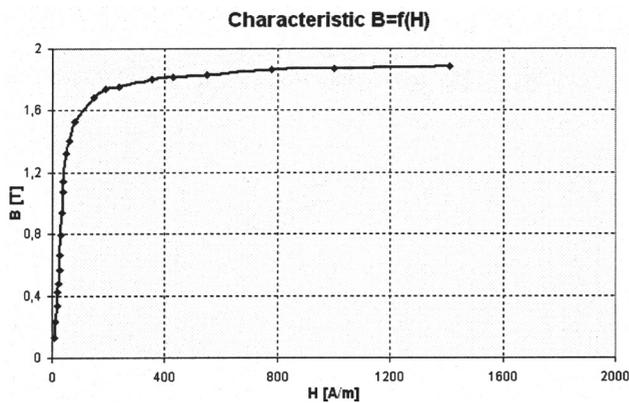


Fig. 2. Magnetizing characteristic for the voltage transformer core

influence of the leakage inductance for the very low number of turns, this characteristic was used to determine the  $B-H$  curve for the core (Fig. 2). The  $U-I$  characteristic for the HV winding can be than directly obtained by re-calculating the characteristic obtained for 60 number. The complete model however, requires realistic values of the leakage inductance as well as of the winding capacitance value and the winding resistance. The  $U-I$  characteristic obtained for the test turns (60) is shown in Figure 1.

Due to negligible influence of the leakage inductance and capacitance (for 60 turns only) this characteristic was used as a basis for re-calculating the characteristic for the HV wiring. The HV  $U-I$  characteristic was obtained by:

- re-calculating the current-fluxlinked ( $I$ -Fluxlinked) characteristic for the required number of turns,
- adding a series resistor representing the winding resistance,
- adding a series linear inductance representing the leakage inductance of the winding,
- adding a parallel capacitor representing the equivalent capacitance of the winding.

Applying the above procedure allowed creating a simulation model of the inductive voltage transformer, in the form presented in Figure 3. The non-linear magnetizing characteristic was implemented using the element TYPE-98.

The verification of the simulation model was done by simulating the currents versus voltage applied ( $U_{peak}$ - $I_{peak}$ ) using the ATP/EMTP software. The simulated  $I_{peak}$  values

corresponding to  $U_{peak}$  voltage levels were then compared against the  $U_{peak}$ - $I_{peak}$  values obtained experimentally before by the laboratory investigation. The comparison is shown in Figure 4.

It can be seen that a very agreement between the measured and simulation was obtained both for the linear region and for the saturated region.

### 3. ATP/EMTP FERRORESONANCE SIMULATIONS

In order to verify the ferroresonant/ non-ferroresonant response of the inductive voltage transformer a simulation model in the ATP/EMTP environment was created. For the sake of ferroresonance simulations the model of the VT was complemented with the resistor representing the iron losses.

The value assumed was  $R_{Fe} = 100 \text{ M}\Omega$  which was corresponding to typical values calculated by laboratory investigation. Since the exact value of the  $R_{Fe}$  depends on the flux density level (a thus on the voltage applied) a simulation model including the non-linear behavior of the resistor was also created, using the TYPE-99 element. The difference between the ferroresonant behavior were between the two model were negligible, which means that the level of the iron losses has in ether of cases a negligible effect on the ferroresonance damping. Therefore in the remaining simulations a linear model of  $R_{Fe}$  was used (Fig. 5).

Except form the non-linear model of the VT the comple simulation model comprises a power source (short-circuit power of 20 MVA was assumed –  $R_s$  and  $L_s$  parameters in the model) and the series capacitance in parallel with the circuit breaker ( $C_W$  in the model). The complete equivalent circuit is shown in Figure 5.

In the simulations the worst-case of the unloaded secondary side of the VT was assumed. The potential ferroresonant-response was screened for various  $C_W$  and network voltage values. The  $C_W$  value for which the ferroresonant response was verified was intentionally broader that the realistic values expected. The selected circuit breaker grading capacitance values  $C_W$  of were:

- 100 pF, 300 pF, 500 pF, 1 nF, 5 nF and 10 nF.

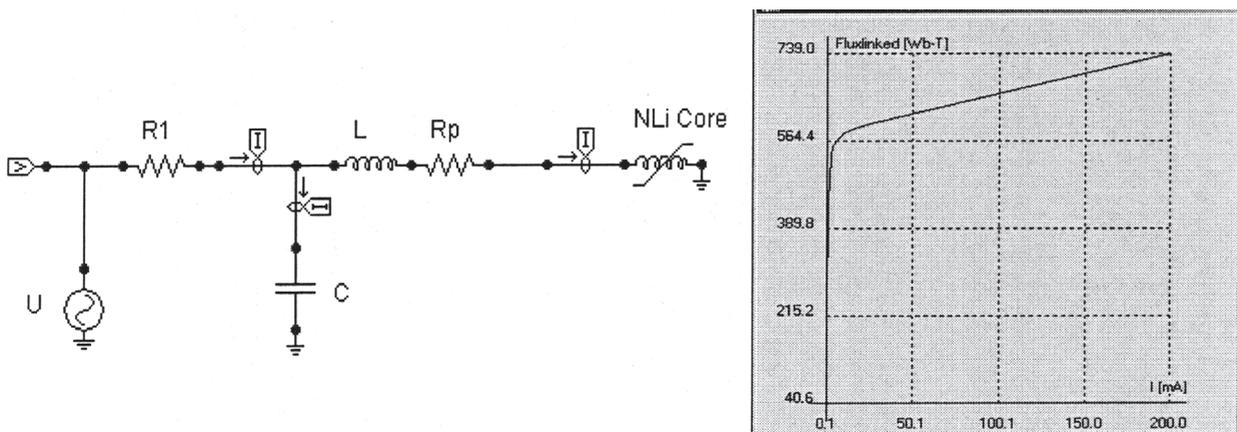


Fig. 3. Complete simulation model of the inductive voltage transformer with HV winding with IVT core non-linear characteristic (magnetizing curve)

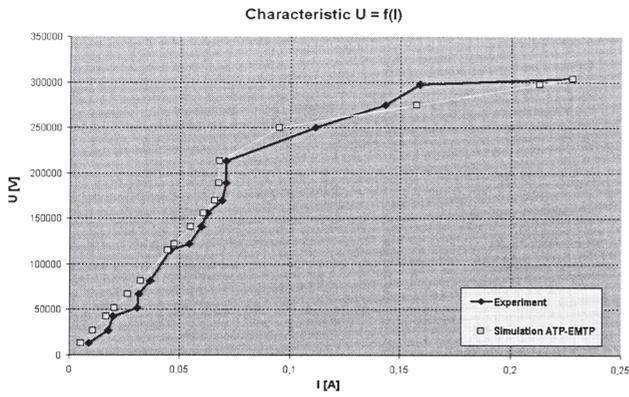


Fig. 4. Comparison between the simulated (green) and measured (blue) Upeak-Ipeak characteristic of inductive voltage transformer

The network voltage values for which the ferroresonance risk was verified were:

- 80%, 100%, 120%, and 150% of the rated voltage  $U_n$  ( $123 \text{ kV} / \sqrt{3}$ ).

The corresponding values of phase-to-ground voltage as well as peak values are summarized in Table 1.

The ferroresonant response was verified for opening a switch parallel to the  $C_W$  at the  $t = 0.5 \text{ s}$ .

In the following sections the results of the transient simulations are shown. For each of the cases voltage at the VT terminal, the primary current and circulates (parallel) inside VT windings current are shown in Figures 6 and 7.

The simulations performed allowed one to identify the ferroresonant combination of  $U_n$  and  $C_W$  values. This ferroresonant region is clearly seen in Table 2, summarizing the results.

Table 1. The network voltage values used in simulations

	Phase-to-phase (RMS)	Phase-to-ground (RMS)	Phase-to-ground (Amplitude)
80% rated voltage	98.4 kV	56.9 kV	80.2 kV
100% rated voltage	123.0 kV	71.1 kV	100.2 kV
120% rated voltage	147.6 kV	85.3 kV	120.3 kV
150% rated voltage	184.5 kV	106.6 kV	150.4 kV

80%  $U_n$ ,  $C_W = 100 \text{ pF}$

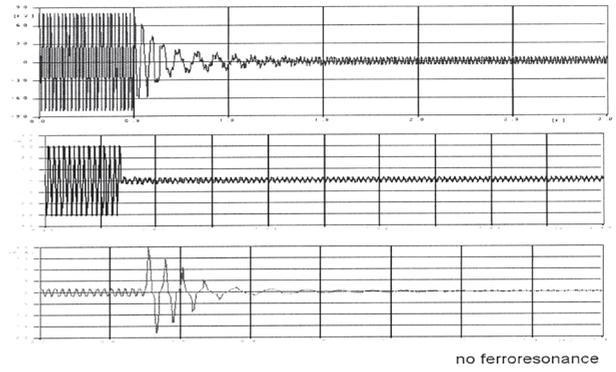


Fig. 6. Exemplary result of transient primary current and voltage at VT terminal for various capacitance of a circuit breaker  $C_W$  and rated voltage  $U_n$  – no ferroresonance case

120%  $U_n$ ,  $C_W = 5 \text{ nF}$

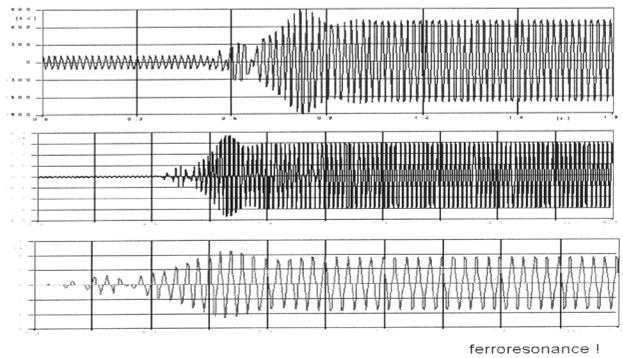


Fig. 7. Exemplary result of transient primary current and voltage at VT terminal for various capacitance of a circuit breaker  $C_W$  and rated voltage  $U_n$  – ferroresonance case

ATP-EMTP model for ferroresonance study

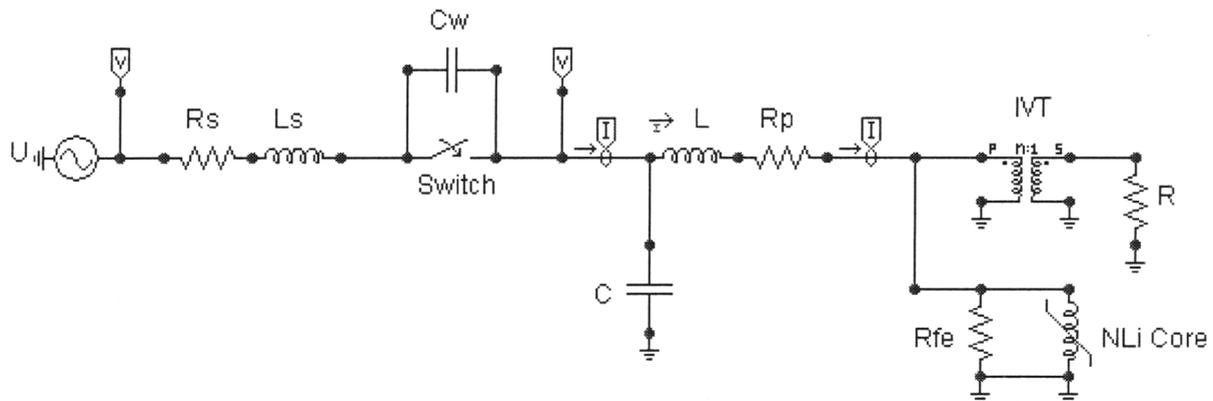


Fig. 5. Complete ATP/EMTP simulation model for ferroresonance study

Table 2. Ferroresonance simulations results summary.

	80% $U_n$	100% $U_n$	120% $U_n$	150% $U_n$
100pF	—	—	—	—
300pF	—	—	—	—
500pF	—	—	—	+
1nF	—	+	+	+
5nF	+	+	+	+
10nF	+	+	+	+

It could be seen that for  $U_n$  values of 100% and higher the ferroresonance may exist for  $C_W = 1\text{nF}$  and above. This value is larger than realistic value of growth capacitance. For lower capacitance values no ferroresonant behaviour was observed. For the extreme value of  $U_n = 150\%$  however, a potential risk of ferroresonance was identified for  $C_W = 500\text{pF}$ .

#### 4. CONCLUSIONS

The analysis presented on the case study example showed the approach applicable to studying the potential of the ferroresonant behavior of the real power devices. Due to the very high sensitivity of the non-linear model behavior to the model accuracy, especially in the deep saturation region, a special care must be taken to accurately modeling of the magnetic circuit. The magnetizing characteristic of the core should be based on the measurements of the real core. The approach utilizing a test winding of low number of turns allows one to minimize the effects of the leakage inductance and stray capacitance. These parameters however must be included in the realistic model of the HV winding.

The use of the ATP/EMTP environment can be used to identify the potential ferroresonant combinations of parameters (voltage and capacitance) and allows one to select appropriate mitigation scheme.

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