

# Mitigating Ferroresonance in HV inductive transformers

W. Piasecki, M. Stosur, M. Florkowski, M. Fulczyk, B. Lewandowski

**Abstract--**Ferroresonant oscillations involving voltage transformers (VTs) may be initiated by transient events such as switching operations or intermittent faults.

In the present article the problem of ferroresonance involving HV VTs is demonstrated with a particular stress on inductive voltage transformers. ATP/EMTP simulations based on a realistic VT model demonstrated that stable ferroresonant oscillations characterized by significant overcurrent values may be initiated by opening a circuit breaker. A new approach towards damping the ferroresonance by means of a compact active damping device is shown. Experimental verification of the device performance proved the ability of effectively damping the ferroresonant oscillations without re-triggering after the load rejection.

**Keywords:** Voltage transformers, ferroresonance damping.

## I. INTRODUCTION

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 in MV networks, and hundreds of kV in HV networks.

In ungrounded networks typically the ferroresonance involves the phase-to-ground connected VTs and the phase to ground capacitances of the lines [2], [4], [7]. In grounded networks the ferroresonant oscillations may involve a single voltage transformer and a series capacitance e.g. a grading capacitance of a circuit breaker [3], [6].

Special construction of voltage transformers characterized by their relatively low power ratings makes them very sensitive to the ferroresonance problem since large overcurrent in the primary windings may lead to the overheating and, in consequence, to the permanent equipment damage.

In MV networks the ferroresonance damping is typically achieved by introducing a damping burden into the open-delta connected auxiliary windings of the VTs [5].

In HV instrument transformers however, ferroresonance free performance is required for each individual device.

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## II. FERRORESONANCE SIMULATIONS

The ATP/EMTP simulations demonstrating the ferroresonance problem in inductive HV Voltage Transformers were performed on the basis of a realistic model of a VT. For the VT model built, the dependence of the ability to initiate the stable ferroresonant oscillations by circuit breaker switching on the grading capacitance value was studied [1],[7].

In order to create an electrical simulation model of the VT, a magnetizing characteristic was measured for the real core of the HV instrument transformer using test windings. Instantaneous current and voltage values were measured using a digital oscilloscope.

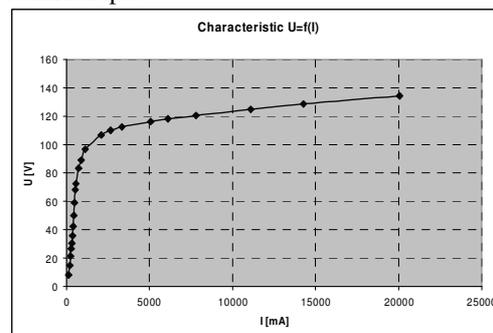


Fig.1. Measured  $U-I$  characteristic for the voltage transformer core

Then the voltage values were re-calculated for real numbers of turns present in the HV device (rated voltage  $123\text{kV}/\sqrt{3}$ ). The  $U-I$  characteristic for the HV winding can be than directly obtained by re-calculating the characteristic obtained from the measurement. 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 winding (60 turns) is shown in Fig. 1. Due to the negligible 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 (see Fig. 2).

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.

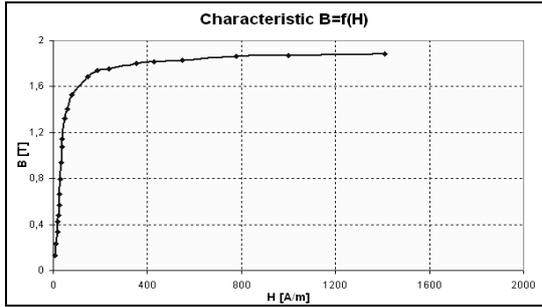


Fig.2. Magnetizing characteristic for the voltage transformer core obtained from the measured  $U$ - $I$  characteristic measured at the test winding

Applying the above procedure allowed one to create a simulation model of the inductive voltage transformer, in the form presented in Fig. 3. The non-linear magnetizing characteristic was implemented using the TYPE-98 [1].

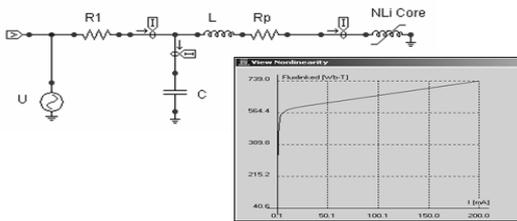


Fig.3. Complete simulation model of the inductive voltage transformer with HV winding with IVT core non-linear characteristic (magnetizing curve). The value  $C$  represents the winding capacitance.

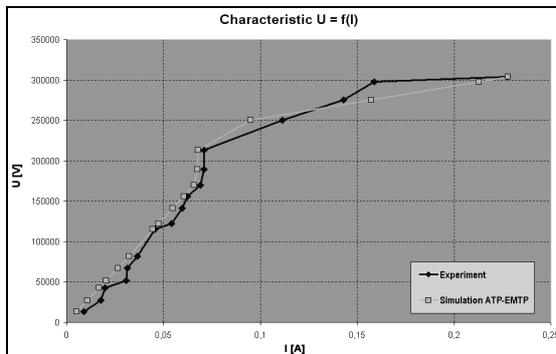


Fig.4. Comparison between the simulated and measured  $U_{peak}$ - $I_{peak}$  characteristic of inductive voltage transformer

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 for a real HV instrument transformer. The comparison is shown in Fig.4.

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

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 (thus on the applied voltage), a simulation model reflecting the non-linear behavior of the resistor was also created. The model comprised the TYPE-99 element [1]. The difference between the ferroresonant behavior between the two models were negligible, which means that the level of the iron losses has in either 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 from the non-linear model of the VT the complex 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 Fig. 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 than the realistic values expected. The selected circuit breaker grading capacitance values  $C_w$  were:

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

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

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

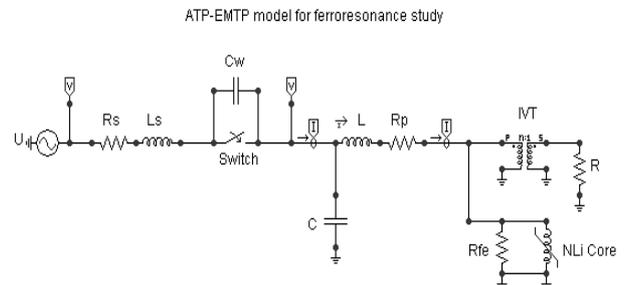


Fig.5. Complete ATP-EMTP simulation model for ferroresonance study [7]

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

For a given voltage level, stable ferroresonant oscillations could be initiated above a certain threshold value of the series  $C_w$  capacitance. This threshold value depended on the voltage level and for higher voltage levels the threshold value was always smaller. Exemplary results of the simulations are shown in Fig. 6. The upper plot presents a non-ferroresonant response to the circuit breaker opening, whereas the lower plot shows the stable ferroresonant oscillations.

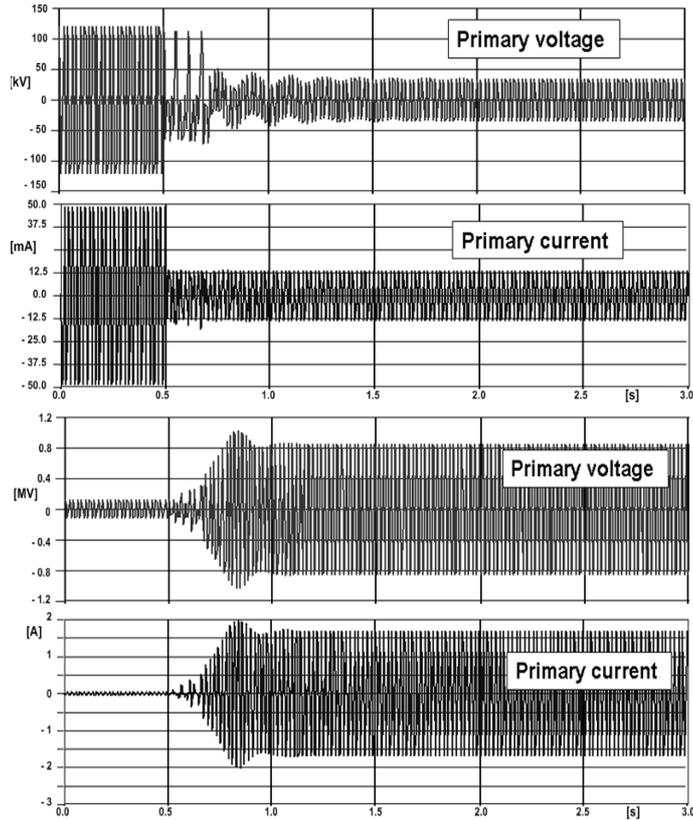


Fig. 6. Exemplary results of transient primary voltage and current at VT terminal for various values of the grading capacitance of the circuit breaker  $C_w$  (Fig. 5) at fixed value of the voltage (120% of  $U_n$  in this case). Upper plot: no ferroresonance, lower plot: ferroresonant oscillations.

TABLE I  
FERRORESONANCE SIMULATIONS RESULTS SUMMARY

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

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 I, summarizing the results.

It could be seen that for  $U_n$  values of 100% and higher the ferroresonance may exist for  $C_w = 1$  nF and above. This value is larger than realistic value of the circuit breaker grading 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  $C_w = 500$  pF.

### III. FERRORESONANCE DAMPING

Effective damping of the ferroresonance in the analyzed case of a HV VT is more difficult than in the typical MV case of three VTs with open-delta connected auxiliary windings [4].

Under normal operating conditions the damping device should be disconnected from the secondary circuit. Upon initiating of the ferroresonant oscillations, however, connecting of the appropriate damping burden to the VT winding should be performed. Disconnecting of the damping burden upon extinguishing of the ferroresonance oscillations, however, may result in re-ignition of the ferroresonant oscillations due to the  $di/dt$  transient in the secondary winding. Therefore a new approach towards damping the ferroresonant oscillations in voltage transformers is shown. The new approach is based on the active (electronic) damping load.

The active damping device developed comprises a ferroresonance detector, using a saturable core reactor whose saturation level is selected so that it saturates at voltage level close to the saturation level of the VT core, for the same frequency. In such a case the current in the reactor can be used for detecting the abnormal situation of reaching the saturation level of the VT core. The device also comprises a resistive damping burden, which could be connected to the terminals of the VT using a solid-state switching element, and a microcontroller circuit. The function of the microcontroller circuit is to provide an appropriate algorithm of controlling the value of the apparent load present at the VT terminals by means of PWM (Pulse Width Modulation) technique.

The functioning of the device comprises the four, clearly distinguishable phases: i) ferroresonance detection, ii) load connection, iii) load maintaining and iv) load rejection.

Special care was taken to optimize the load rejection phase so the ferroresonance was not re-triggered.

The ability of effectively damping the ferroresonant oscillations without the risk of re-triggering was demonstrated experimentally.

For the sake of simplification of the experiment a low-voltage equivalent set-up was used. The voltage transformer used in the experiment was prepared so that it comprised a real core and the low voltage winding of the real VT. The high voltage winding, however was replaced with a winding comprising a small number of turns only, so that nominal flux density in the core could be achieved already at LV level applied to the primary winding (140 V only). For the VT used in the experiment with the winding comprising  $n$ -times smaller number of turns, the circuit breaker capacitance  $C_w$  and the winding capacitance  $C$  values corresponding to the HV side of the real VT had to be scaled up with a factor of  $n^2$ .

The schematic diagram of the experimental set-up is shown in Fig. 7. The ferroresonance was initiated by opening the switch representing the circuit breaker.

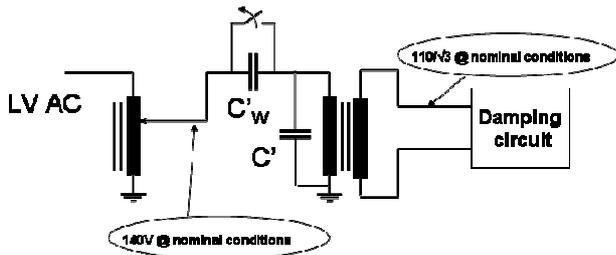


Fig. 7. Experimental set-up comprising the LV adjustable voltage source, the VT, adjustable capacitors representing the circuit breaker and winding capacitances, the switch, and the damping device connected to the secondary VT winding.

A typical example of the recorded primary current and primary voltage of the VT is shown in Fig. 8.

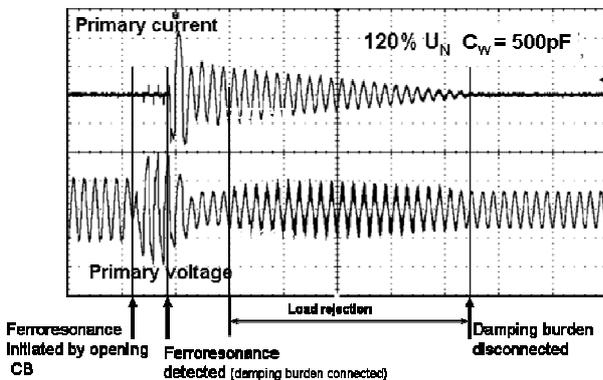


Fig. 8. Ferroresonance damping in HV VT using the active damping device

In this particular case the series capacitance value used corresponded to the value of 500 pF at the 123 kV level and the voltage level corresponded to 120% of the nominal system voltage. Upon opening of the circuit breaker the series capacitance is introduced to the circuit and the ferroresonant oscillations are initiated. The primary voltage increases above the saturation level and the primary current peaks are visible. Upon the detection of the ferroresonance the load is connected to the VT terminals and then gradually rejected. This can be seen in Fig. 7 as the initially high current in the VT primary winding resulting from the loading of the secondary winding gradually decreases. As also seen in Fig. 8 the system remains stable after completing of the load rejection phase.

Experiments performed up to 150% of the nominal system voltage and for capacitances equivalent to up to 10 nF confirmed the ability of the active device developed to successfully damp the ferroresonance oscillations without re-triggering after the completion of the load rejection.

#### IV. CONCLUSIONS

Ferroresonant oscillations involving inductive VTs may be initiated by transient events such as switching operations.

The analysis presented showed that in a typical inductive VT the ferroresonant oscillations involving the CB grading capacitance may exist for certain combinations of the capacitance value and the actual network voltage. Due to 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 ATP-EMTP environment was successfully used to identify the potential ferroresonant combinations of parameters (voltage and capacitance). The results obtained allowed one to optimize the damping scheme and to build an active damping device which detects the ferroresonant oscillations in the VT, connects the damping burden to the VT terminals, and then gradually rejects the load, avoiding ferroresonance re-triggering. Experiments performed using a LV testing environment comprising a real HV VT magnetic circuit proved the ability of the device developed to effectively damp the ferroresonant oscillations for any realistic combination of the network voltage and the grading capacitance value.

#### V. REFERENCES

- [1] H.W. Dommel, "Electromagnetic Transients Program," *Reference Manual (EMTP) Theory Book*, BPA, Portland, Oregon, 1986.
- [2] Ph. Ferracci, "Ferroresonance," *Cahiers Techniques Schneider*, Collection Technique Groupe Schneider, No. 190, 1998.
- [3] M. Val Escudero, I. Dudurych, M.A. Redfern, "Characterization of Ferroresonant Modes in HV Substation with CB Grading Capacitors," *VIth Int. Conf. on Power Systems Transients*, no.146, 2005.
- [4] W. Piasecki, M. Florkowski, M. Fulczyk, P. Mahonen, M. Luto, W. Nowak, "Ferroresonance Involving Voltage Transformers in Medium Voltage Networks," *XIVth Inter. Symp. on the High Voltage Engineering*, Tsinghua University Beijing, F-19, 2005.
- [5] M. Graovac, R. Iravani, X. Wang, R.D. McTaggart, "Fast Ferroresonance Suppression of Coupling Capacitor Voltage Transformers," *IEEE Trans. on Power Delivery*, vol. 18, no. 1, pp.158-163, 2003.
- [6] M. Sanaye-Pasand, R. Aghazadeh, H. Mohseni, "Ferroresonance Occurrence during Energization of Capacitive Voltage Substations," *IEEE Power Engineering Society General Meeting*, pp. 601-606, 2003.
- [7] M. Stosur, W. Piasecki, M. Florkowski, M. Fulczyk, B. Lewandowski, "Ferroresonance study for a HV inductive voltage transformer using ATP-EMTP," *European EMTP-ATP Conference*, European EMTP-ATP Users Group Association, Leon, Spain, pp. 113-119, Sept. 2007.

#### VI. BIOGRAPHIES

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