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and

*The Second „International Symposium on High Voltage and High Power Tests, Measurements  
and Qualification of Electric Power Equipment"  
SIMC - EE 2004*

# SYMPOSIUM SECTIONS

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Round-Table discussion “**Outlook on the future of Romanian Electric Industry**”, organised under the aegis of Electrical and Power Engineering Section of ASTR - The Romanian Technical Sciences Academy, with the kind support of Romanian Academy, Ministry of Economy and Commerce, Ministry of Education and Research, Romanian National Committee for IEC, AGIR - The General Association of the Engineers in Romania.

*Moderator: Prof. Dr. Eng. Florin Theodor Tănăsescu*

## SECTION I: Test and Measuring/Calibration Techniques related to High Voltage Laboratories

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### **I.1. Electrical Insulation Tests on the Modular 400 kV/AC Lead Exit System for Power Transformers**

*Heinrich Bernhard, Krause Christoph – WEIDMANN Transformerboard Systems AG, Rapperswil, Switzerland; Wick Kurt – WEIDMANN Systems International AG, Rapperswil, Switzerland*

### **I.2. An Unconventional Test of Autotransformer 400 MVA, 400/231/10.5 kV Ynad5**

*Jankovic Aleksandar - ELEKTROISTOK, Serbia; Beric Vladimir - MINEL Transformatori, Serbia; Marinescu Andrei, Popa Dorin, Ungureanu Aurel – ICMET Craiova, Romania*

### **I.3. On-Site Synchronous Multi-Terminal Partial Discharge Measurements on Power Transformers**

*Schaper Stefan, Kalkner Wilfried – TU Berlin, Germany; Plath Ronald – IPH Berlin, Germany  
Marinescu Andrei – ICMET Craiova, Romania*

#### **I.4. Instrumentation & Concept of Partial Discharge and Temperature Cable Monitoring**

*Strehl Thomas – Lemke Diagnostics GmbH, Germany*

#### **I.5. Type Test and Calibration of 200 MS – 14 bit Digital Recorder for Impulse Voltage Tests and their Application for Frequency Response Analysis**

*Strauss Werner, Steiner Thomas, Dr. Strauss System-Elektronik GmbH, Germany*

#### **I.6. Operational Principles and Selection Criteria for On-Load Tap-Changers**

*Carlsson Mats – ABB, Sweden*

#### **I.7. Results of the Measurements Performed in European DKD Accredited HV Laboratories to Qualify a Transfer Standard**

*Schon Klaus, Lucas Wolfgang, Marx Rainer – PTB, Braunschweig, Germany; Marinescu Andrei, Popa Dorin, Ungureanu Aurel, Dumbravă Ionel, Vascan Teodor – ICMET Craiova, Romania*

#### **I.8. The High Voltage Laboratories of the University „Politehnica”- Bucharest**

*Drăgan Gleb, Romanian Academ, Romania*

#### **I.9. A Comparative Analysis between Streamer and Leader**

*Drăgan Gleb – Roumanian Academy, Romania*

#### **I.10. Measuring of Radio Interference Voltages Due to Insulator Sets for High Voltage Lines TICEM-HV Laboratory Experience**

*Coatu S., Costea D., Rucinski D., Băran Ileana, Cristea V., Leonida T. – Politehnica University of Bucharest, Romania*

#### **I.11. Measuring Domain Extension of the 30 kV Electrostatic Voltmeter and Disturbances**

*Titihăzan Viorel, Titihăzan Mariana, Toader Dumitru – University Politehnica Timișoara, Romania  
Curcanu George – ICMET Craiova, Romania; Cimponeriu Andrei – SC SIEMENS VDO Timișoara, Romania; Iuhasz Iosif – TRANSELECTRICA Timișoara, Romania*

#### **I.12. Modeling Lightning Surges in Power Transformer**

*Cividjian Grigore, Dolan Alin – University of Craiova, Romania; Călin Gheorghe, Popa Dorin – ICMET Craiova, Romania*

#### **I.13. Reference Measuring System for DC, AC and Impulse High Voltages**

*Coatu S., Costea M., Rucinski D. – Politehnica University of Bucharest, Romania  
Marinescu Andrei, Popa Dorin, Ungureanu Aurel, Vascan Teodor – ICMET Craiova, Romania*

#### **I.14. Methods of Optimizing the Optic Link used at Transmitting the Information from the Primary Circuit to the Secondary One of the Non-Magnetic Core Power Transformers**

*Niculescu Sorin – Transelectrica Co., Branch Craiova, Romania*

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*Stancu Iulian, Stancu Octavian – Trafo Proiect SRL Bucharest, Romania*

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*Marinescu Andrei, Călin Gheorghe – ICMET Craiova, Romania; Stancu Iulian, Stancu Octavian – SCANDO, Romania*

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*Popa Dorin, Vascan Teodor, Ungureanu Aurel, Urzică Florinel, Badea Ion – ICMET Craiova, Romania*

#### **I.18. Study of Temperature Distribution in Capacitor-Type Bushings**

*Nedelcuț Dorel – ICMET Craiova, Romania; Bică Marin, Țălu Mihai – Faculty of Mechanics, Craiova, Romania*

#### **I.19. A Mobile Calibration Laboratory for DC, AC, LI and SI High Voltage Measuring System Calibration**

*Marinescu Andrei, Popa Dorin, Ungureanu Aurel, Dumbravă Ionel – ICMET Craiova, Romania*

#### **I.20. Considerations on the Shed Shape of Composite-Type Insulators for Overhead Lines**

*Nedelcuț Dorel, Păduraru Nicolae – ICMET Craiova, Romania*

# MODELING LIGHTNING SURGES IN POWER TRANSFORMERS

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**Abstract** – Using FEM, the self and mutual inductances of all the windings of a three phase power autotransformer and their partial capacitances are determined and used to explain the early observed lightning over voltages on the free end of regulating winding.

## 1. INTRODUCTION

High voltage (HV) and high power (HP) transformer / autotransformer stressing with impulse voltage or high frequency (HF) oscillating voltages is a complex phenomenon depending mainly on the intrinsic characteristics of the windings and on their connections.

At impulse voltage as well as when applying some HF oscillating voltages the windings behave as a complex R-L-C network the elements of which are frequency dependent reason why the voltages appearing in different points of the windings have wave shapes completely different from the ones of the applied voltages, even their peak values being affected. Consequently, on the regulating taps and on on-load tap changer plots important overvoltages can appear and their maximum values greatly exceed the maximum value of the incident voltage.

L – C model study of the processes taking place in transformer winding during voltage impulse testing renders evident the model possibility to identify constructive parameter influence on the level of the voltage impulse generated stresses.

## 2. INFLUENCE OF SHORT-CIRCUITED TERTIARY WINDING

Denoting by  $\hat{I}$  the amplitude of the current in the  $w$  turns winding, by  $\Phi$  the magnetic flux in the core, by  $r$  and  $x = \omega w^2 \Lambda_s$  the resistance and the leakage reactance of tertiary winding, by  $\omega = 2\pi f$  frequency of magnetic field and  $\Lambda_s$  the leakage permeance, the magnetic impedance of the transformer core with short-circuited tertiary winding will be:

$$Z_{sc} = \frac{w \hat{I}}{\Phi} = R_{sc} + j X_{sc}$$

$$R_{sc} = \frac{\omega w^2 x}{r^2 + x^2} \quad (1)$$

$$X_{sc} = \frac{\omega w^2 r}{r^2 + x^2}$$

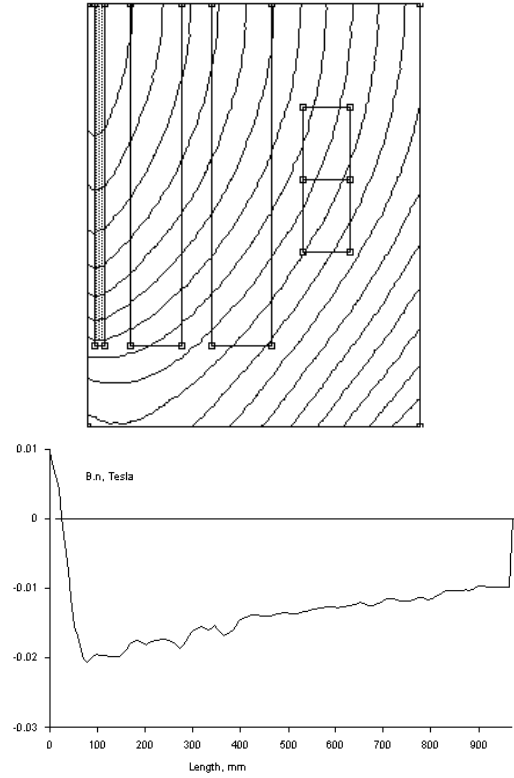


Figure 1: Axisymmetric solution for short-circuited tertiary winding (FEMM)

Mesh size 20, 3128 nodes, 6024 elements  
 Current density 0.8 A/mm<sup>2</sup>  
 Total current 25600 A  
 Magnetic field energy 678.6 J  
 Leakage inductance 12.08 mH  
 $\Lambda_s \approx 1 \mu\text{H}$

The permeance of the S - cross-section core-with open winding is given by the average relative permeability  $\mu$  of the core:

$$\Lambda_0 = \frac{\mu_0 \mu S}{l_{fe}} \quad (2)$$

The equivalent permeance of the core with short-circuited winding at frequency  $\omega$  results from the equation:

$$\frac{1}{\Lambda_e} = \frac{1}{\Lambda_0} + R_{sc} \Rightarrow$$

$$\Lambda_e = \Lambda_s \frac{1+u^2}{1 + \frac{\Lambda_s}{\Lambda_0}(1+u^2)} \quad (3)$$

where  $u = \frac{r}{x}$ .

In particular, for high frequency and large core cross-section,  $u$  as well as  $\Lambda_s/\Lambda_0$  tend to zero and the equivalent permeance approaches the leakage permeance  $\Lambda_s$ . This leakage permeance can be determined using the magnetic field energy or directly magnetic flux linkage, obtained by solving the magnetic field in the transformer window and in frontal part of the winding.

In our case  $r = 0.31 \Omega$  at 14 kHz,  $x = 1100 \Omega$ ,  $\Lambda_s = 1 \mu\text{H}$ ,  $\Lambda_0 = 90 \mu\text{H}$  for  $\mu = 1000$ .

This means that practically all the magnetic flux avoid the core and closes in air. The same is thru for the magnetic flux produced by all the currents in other windings. Each current in a winding produces an eddy current in the short-circuited tertiary winding, reducing practically to zero the magnetic flux thru the core. All the self and mutual inductances will be calculated in these conditions.

### 3. SELF AND MUTUAL INDUCTANCES FOR SHORT-CIRCUITED TERTIARY WINDING

The self and mutually inductances was calculated using the solved by FMM magnetic field in the transformer window in the case of short-circuited (and grounded) tertiary winding. The results obtained for external part of the windings, taking into account the ferromagnetic tank, are very close to them and no showed. The two inductances are given by the equations:

$$L_1 = \frac{\iiint_{S_1} A j_1 dV}{I_1^2}; \quad M_{12} = w_2 \frac{\iiint_{S_2} A dV}{I_1} \quad (4)$$

where  $A$  is the vector potential of the magnetic field,  $j_1$  and  $I_1$  the current density in coil 1 cross-section  $S_1$  and the current in the coil 1,  $w_2$  and  $S_2$  the turns density and the cross-section of the coil 2.

Using the turns density from Table 1, the results obtained for self and mutually inductances are shown in Table 2, 3 and 4.

Turns density	T	LV	HV	R
$W[\text{m}^{-2}]$	1688	2183	2769	5076

Table 1: Turns density of the windings

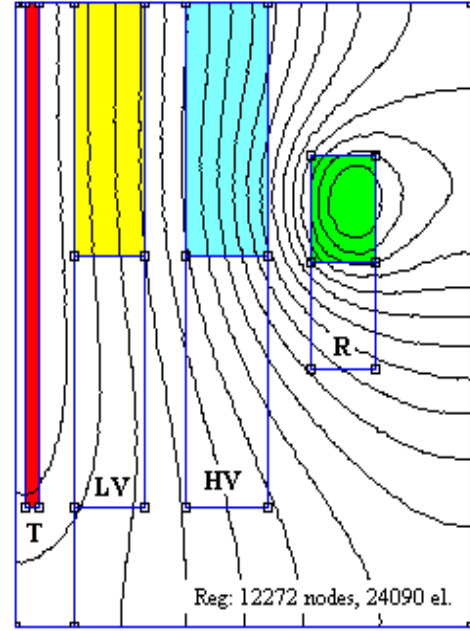


Figure 2: Magnetic field pattern for current injected in upper half of regulating winding

Current	A	290
Ampere turns	kA	43.8
Current densities	$\text{A}/\text{mm}^2$	1.47; -1.37
$\iiint_{R/2} A j dV$	J	10208
$\iiint_{HV/2} A dV$	$\text{mWb}\cdot\text{m}^2$	9.34
$\iiint_{LV/2} A dV$	$\text{mWb}\cdot\text{m}^2$	2.53
$L_{R/2}$	mH	122
$M_{R/2-HV/2}$	mH	137
$M_{R/2-LV/2}$	mH	19

Table 2: Calculated parameters and their values for current injected in upper half of regulating winding

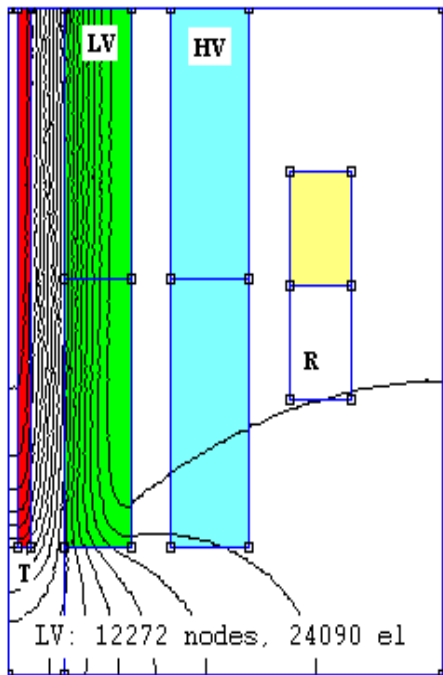


Figure 3: Magnetic field pattern for current injected in low voltage winding

Current	A	578
Ampere turns	kA	189.3
Current densities	A/mm <sup>2</sup>	1.262; -5.914
$\iiint_{LV} A j dV$	J	23295
$\iiint_{R/2} A dV$	mWb·m <sup>2</sup>	4.29
$\iiint_{HV} A dV$	mWb·m <sup>2</sup>	24.82
$L_{LV}$	mH	69.76
$M_{LV-R/2}$	mH	37.6
$M_{HV-LV}$	mH	118.9

Table 3: Calculated parameters and their values for current injected in low voltage winding

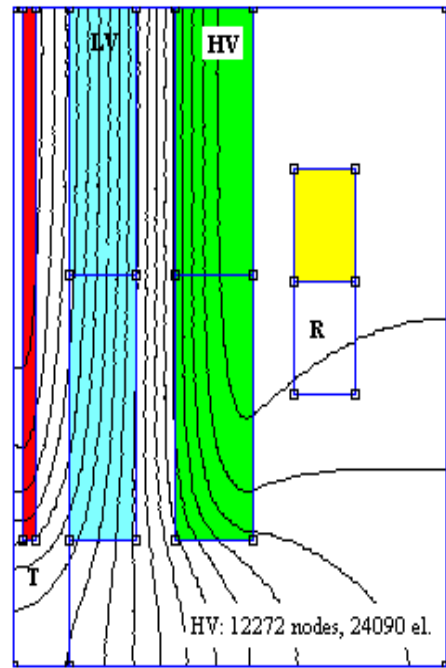


Figure 4: Magnetic field pattern for current injected in high voltage winding

Current	A	289
Ampere turns	kA	138.4
Current densities	A/mm <sup>2</sup>	0.8 ; -4.325
$\iiint_{HV} A j dV$	J	39835
$\iiint_{R/2} A dV$	mWb·m <sup>2</sup>	9.417
$\iiint_{LV} A dV$	mWb·m <sup>2</sup>	17.244
$L_{HV}$	mH	477
$M_{HV-R/2}$	mH	165.4
$M_{HV-LV}$	mH	130

Table 4: Calculated parameters and their values for current injected in high voltage winding

#### 4. CAPACITANCE OF A PAIR OF INTERLINKED WINDING DISKS

Denoting by  $C$  the capacitance between two adjacent turns, the equivalent capacitance of two disks with  $2n$  turns ( $n$  turns of each disk) results from the equality of electric energies stocked in wires capacitances and the equivalent capacitance of the two

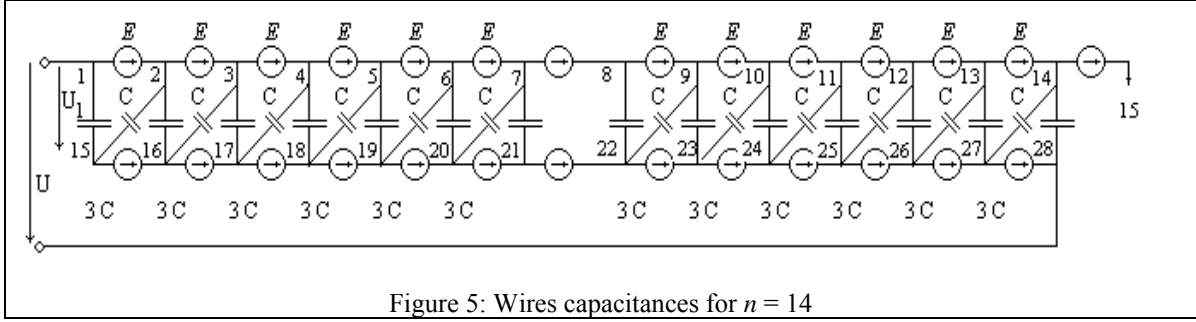


Figure 5: Wires capacitances for  $n = 14$

disks (fig. 5):

$$\left[ 3nU_1^2 + (n-2)U_2^2 \right] \frac{C}{2} = C_e \frac{U^2}{2}$$

$$U_1 = \frac{n}{2n-1} U$$

$$U_2 = \frac{n-1}{2n-1} U$$
(5)

The equivalent capacitance of two disks will be:

$$C_e = \frac{2n^2 - n + 2}{2n-1} C$$

$$C = \varepsilon_0 \varepsilon_p \pi D_m \frac{h_c}{\delta_i}$$
(6)

where  $\varepsilon_p \approx 3.8$

Here  $\delta_i$  is the conductor insulation double thickness,  $\varepsilon_p$  is the transformer paper relative dielectric permittivity,  $h_c$  – the conductor height.

For a winding with  $N$  disks the equivalent axial capacitance will be:

$$C_{eN} = \frac{2}{N} C_e = \frac{2(2n^2 - n + 2)}{(2n-1)N} C$$
(7)

The longitudinal winding capacitances, determined with above formula, considering only the adjacent wires capacitances and neglecting the capacitances between the wires situated in different disks, are the following:

High voltage winding	Low voltage winding	Regulating winding
1050 m·pF	537 m·pF	183 m·pF

Table 5: Specific longitudinal equivalent wires capacitances

## 5. SIMPLE SCHEME FOR LIGHTING SURGE EVALUATION ON FREE END OF REGULATING WINDING

We can neglect, in first approximation, the mutual inductances between the regulating winding and low voltage winding, because of relatively low value (2 x 19 mH) and of the screening effect of the high voltage winding, situated between them. We will neglect also the mutual inductance between high and low voltage windings. In these conditions, we can consider a very simple scheme Simp3 from the fig. 6, which was analyzed with ATP program. The theoretical results are given in fig. 7.

In the next table is given the comparison with experimental data. The large differences are probably the result of the assumptions.

	$u_{\max}$	$u_{\min}$	$(u_1 - u_2)_{\max}$	$t_{\min}$
Experim	40 V	-220 V	340 V	34.5 $\mu$ s
Calc.	29 V	-162 V	290 V	30.0 $\mu$ s

Table 6: Experimental and calculated results

## 6. CONCLUSIONS

1. The characteristic length of the lumped elements necessary for consideration is of the order of 20-50 cm.
2. The simplified scheme can be used to identify the influence of the constructive parameters of the autotransformer on the level and the frequency of lighting surges.

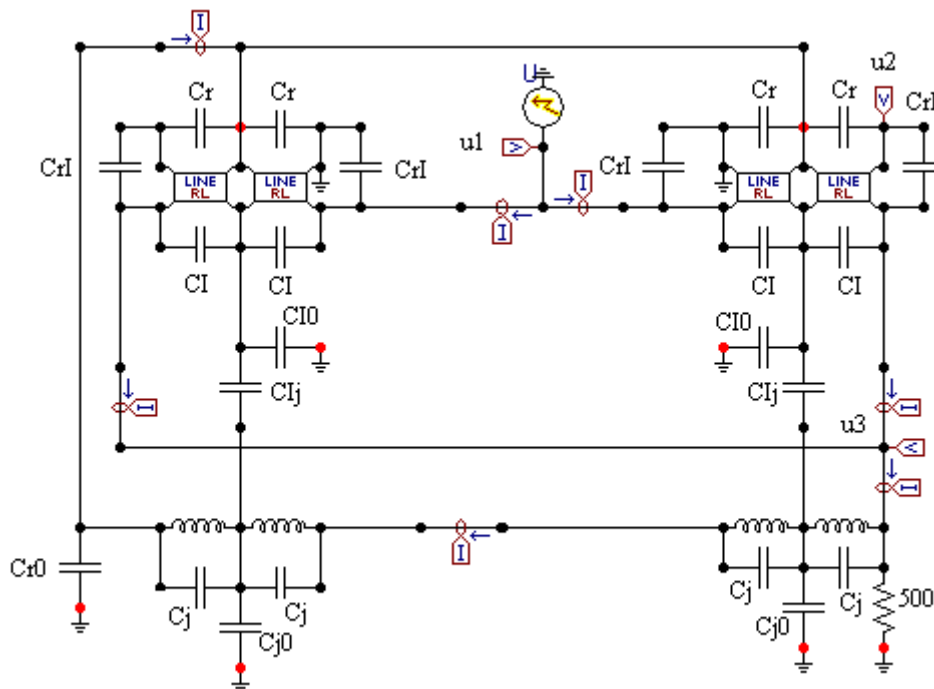


Figure 6: Simplified scheme of transformer windings

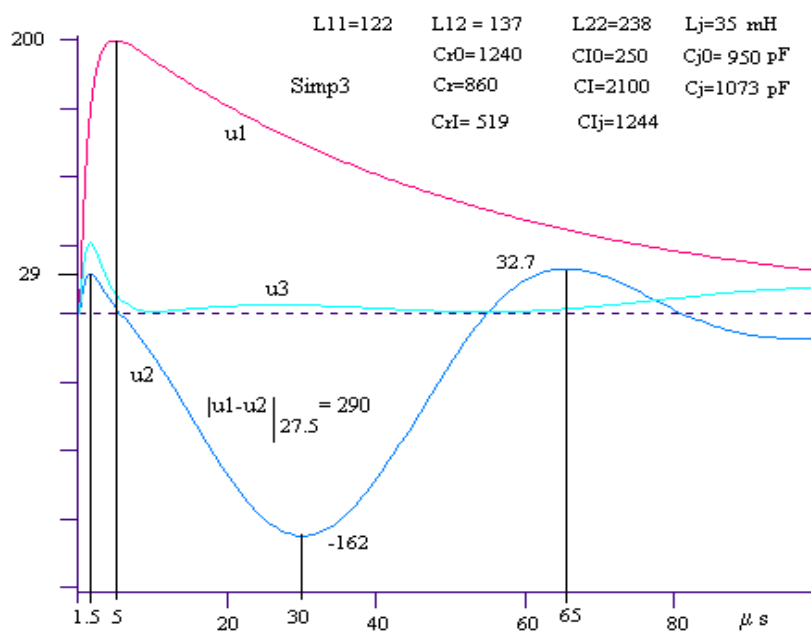


Figure 7: Lighting surge in free end of regulating winding and in the common terminal  $A_2$  ( $u_2$  point and respectively  $u_3$  point from simplified scheme).



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