Transient analysis of special transformers coupled with Finite Element Method

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The paper presents a numerical method based on the finite elements to model the electromagnetic phenomena in two different special transformers. 2D FEMM model of existing resistance welding transformer will be verified with experimental test results. The combined instrument transformer will be modeled and calculated with original FEM-3D program developed at the Faculty of Electrical Engineering and Information Technologies - Skopje. The FEM results will be coupled with originally developed transformer transient model. The test results obtained for the real resistance welding transformer will be used to verify the performance of the developed transient model. Next, the verified model will be used for metrological analysis of the combined instrument transformer.

1. Introduction

In the analysis of electromagnetic devices, including transformers, the problems are almost always nonlinear due to the presence of ferromagnetic materials. The special transformers, like resistance welding transformer (RWT) or combined current-voltage instrument transformer (CCVIT) are complex non-linear electromagnetic systems which operate in transient working regimes. Resistance welding transformers (RWT) unlike the power transformers, always operate with low duty factor, adopting high values of the flux and the current density. In such case the nonlinearity of the transformer core is even more emphasized.

The CCVIT must comply with the rigorous metrological specifications of the IEC 60044-2 standard [1] during the transient regimes.

The analyzed devices are heterogeneous and most appropriately are studied by numerical methods. Modern Maxwell's equations engineering represented often by Finite Element Method (FEM) analysis, achieves very good results in the analysis of electrical engineering problems. A straightforward application of the FEM numerical modeling is to examine the electromagnetic behavior of the transformer under different working conditions.

In this paper 2D FEMM [2] model of existing resistance welding transformer will be verified with experimental test results. The magnetic field analysis of the CCVIT will be done by an original and universal program package FEM-3D developed at the FEIT-Skopje, [3]. The results of the FEM analysis will be input data in a dynamic transformer model for transient analysis. The core saturation will be incorporated in the model as in [4] by using the relationship between measured saturated and unsaturated values of mutual flux.

2. FEM analysis

The magnetic field distribution is most properly calculated by using the Poisson's nonlinear partial differential variable coefficient type equation (1).

$$\frac{\partial}{\partial x}\left(\vec{\nu}(\vec{B})\frac{\partial \vec{A}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\vec{\nu}(\vec{B})\frac{\partial \vec{A}}{\partial y}\right) + \frac{\partial}{\partial z}\left(\vec{\nu}(\vec{B})\frac{\partial \vec{A}}{\partial z}\right) = -\vec{j}(x,y,z) \quad (1)$$

Although 3D calculations belong to the present state of possibilities, 2D calculations are still preferred to obtain an accurate solution in a reasonable time. In this case, 2D FEM model of an actual RWT has been derived. According to the manufacturer data and the measurements performed, the resistance welding transformer has the following rated data: primary voltage 380 V; secondary no-load voltage (1,41 – 4,63) V; conventional power 24 kVA; rated frequency 50 Hz; thyristor controlled switching; number of primary tap positions 9. The transformer is a single phase with shell type core.

The FEMM magnetic field distribution of the RWT at nominal position 8, as well as the variation of the core flux density for different working conditions is presented in Fig. 1.

Once the distribution of the field is available, the postprocessor calculation of the total current losses, iron losses, magnetic field energy and transformer inductance has been performed. These quantities form the base for the nonlinear analysis of the electromagnetic phenomena in the transformer. Table I compares FEM calculations with available test data for the RWT. As can be seen from Table I the agreement between the experiment and the numerical results is excellent, approving the derived numerical model as valid and accurate. The leakage reactances of the RWT were calculated by using the FEMM program and they served as input in the dynamic model.
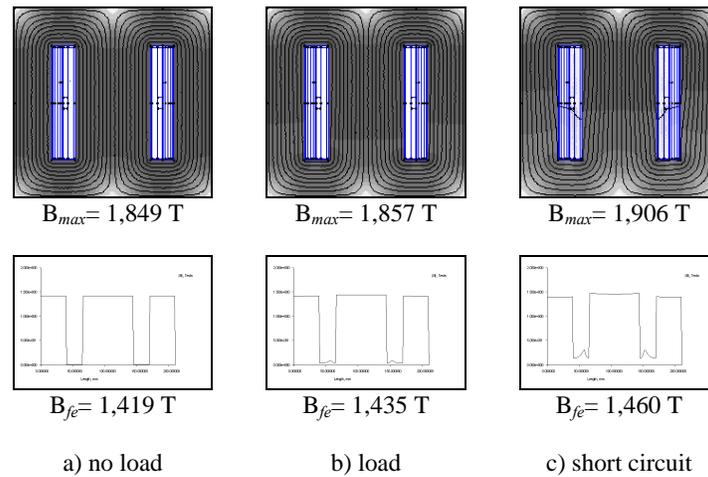
| B$_{max}$= 1,849 T | B$_{max}$= 1,857 T | B$_{max}$= 1,906 T |

| B$_{fe}$= 1,419 T | B$_{fe}$= 1,435 T | B$_{fe}$= 1,460 T |

a) no load   b) load   c) short circuit

Fig. 1. Resistance welding transformer field distribution

Table 1. RWT flux density and copper losses.

	measured	FEM calculated	relative error
core flux density [T]	1.418	1.435	1.20 %
copper losses [W]	7013	7320	4.38 %

The second object of this analysis is a 20 kV combined current-voltage instrument transformer. The CCVIT is a complex electromagnetic device with two measurement cores: voltage measurement core (VMC) and current measurement core (CMC) with four windings and two magnetic cores with mutual non-linear electromagnetic influence in one housing (VMC ratio $(20000V / \sqrt{3}) : (100V / \sqrt{3})$ and CMC ratio 100 A: 5 A) as displayed in Figure 2.
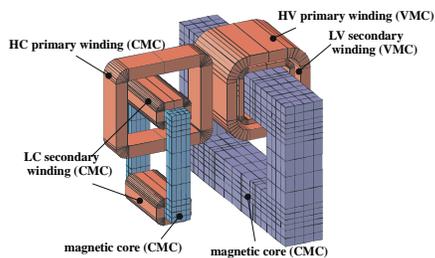

Fig. 2. Three-dimensional display of the electromagnetic system active parts of the combined current-voltage instrument transforme.

Because of the very high complexity of the CCVIT electromagnetic system three-dimensional magnetic field study has to be performed in order to achieve the most relevant electromagnetic parameters. A universal and original program package FEM-3D developed at the Faculty of Electrical Engineering and Information Technologies has been used for this purpose. The CCVIT three-dimensional domain has been divided into 19 cross-sectional layers along the z-axis with permanent electrical and magnetic properties. The FEM-3D iterative calculation has been done for different working conditions of the both measurement cores: from plug-out regime to 1,2 of the rated voltages and currents of VMC and CMC. The magnetic field distribution of the CCVIT, calculated by FEM-3D in the 19 cross-sectional layers along the z-axis of the 3D domain for two extreme working regimes is presented in Figs. 3 and 4. A thorough steady-state FEM-3D CCVIT analysis has been given in [5].
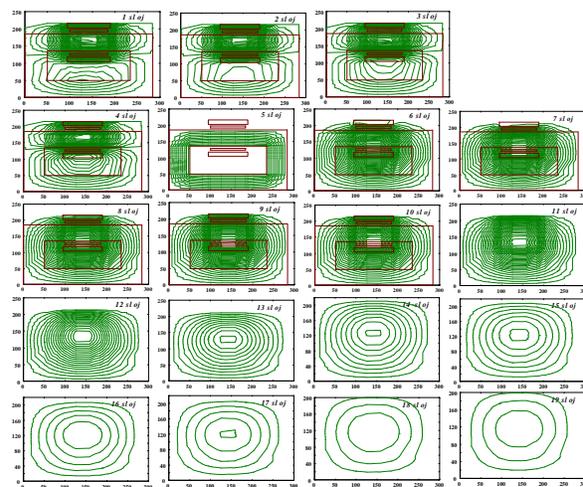

Fig. 3. CCVIT magnetic field distribution (without CMC load) at rated VMC voltage (equidistance ΔA=0,00001 [Wb/m]).

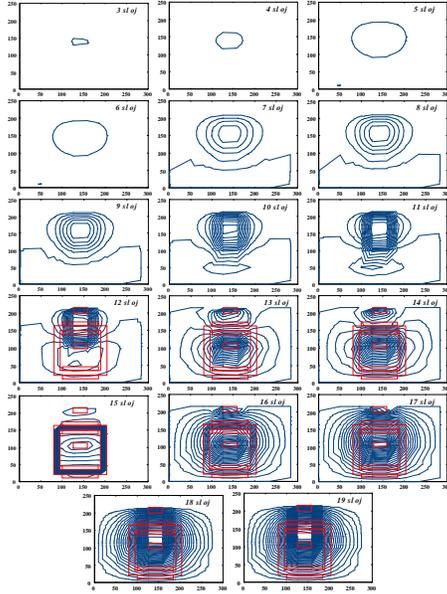Fig. 4. CCVIT magnetic field distribution (without VMC load) at rated CMC current (equidistance ΔA=0,0001 [Wb/m]) Note: at this equidistance there are no equipotential lines in the first and the second cross-sectional layer along the z-axis of CCVIT 3D domain

The FEM post-processing results, e. g. leakage reactance characteristics are input data into the non-linear mathematical model of the RWT and CCVIT. Leakage reactance of RWT has been found to be 0.037 Ω. The FEM-3D calculated leakage reactances per turn of each of the four CCVIT winding for the most important working regimes of the both cores are given in Tables 2 and 3.

Table 2. CCVIT leakage reactances of the VMC per turn.

$\frac{U_u}{U_{nu}}$	Only VMC	0	0.2	0.4	0.6	0.8	1.0	1.2	Only VMC	0	0.2	0.4	0.6	0.8	1.0	1.2
$\frac{I_i}{I_{ni}}$	$x_{\sigma 1eu}$ [μΩ]								$x_{\sigma 2eu}$ [μΩ]							
0.2	91.61	91.22	83.48	69.41	58.30	47.10	36.16	25.30	63.58	63.31	57.94	48.17	40.46	32.69	25.10	17.56
0.4	92.12	92.09	86.56	81.01	75.46	69.84	64.38	59.00	63.93	63.91	60.07	56.22	52.37	48.47	44.68	40.95
0.6	91.28	91.29	87.61	83.88	80.19	76.48	72.78	69.22	63.35	63.35	60.80	58.21	55.66	53.08	50.51	48.04
0.8	91.51	91.49	88.73	85.97	83.17	80.40	77.62	74.95	63.51	63.49	61.58	59.66	57.72	55.80	53.87	52.02
1.0	91.61	91.64	89.40	88.20	84.97	82.74	80.54	78.39	63.58	63.60	62.04	61.21	58.97	57.42	55.89	54.40
1.2	91.81	91.79	89.95	88.11	86.26	84.40	82.54	80.78	63.72	63.71	62.43	61.15	59.87	58.58	57.28	56.06

Table 3. CCVIT leakage reactances of the CMC per turn.

$\frac{I_i}{I_{ni}}$	Only CMC	0	0.2	0.4	0.6	0.8	1.0	1.2	Only CMC	0	0.2	0.4	0.6	0.8	1.0	1.2
$\frac{U_u}{U_{nu}}$	$x_{\sigma 1ei}$ [μΩ]								$x_{\sigma 2ei}$ [μΩ]							
0.2	28.09	27.75	27.47	27.21	26.91	26.68	26.39	26.18	8.910	8.801	8.713	8.630	8.537	8.462	8.370	8.305
0.4	28.10	27.76	27.62	27.50	27.35	27.21	27.09	26.96	8.913	8.806	8.760	8.723	8.676	8.630	8.592	8.551
0.6	28.09	27.75	27.67	27.58	27.48	27.39	27.30	27.22	8.911	8.803	8.775	8.747	8.716	8.688	8.661	8.633
0.8	28.11	27.76	27.70	27.63	27.56	27.49	27.43	27.37	8.915	8.806	8.785	8.764	8.741	8.720	8.699	8.681
1.0	28.10	27.75	27.69	27.64	27.58	27.52	27.48	27.42	8.914	8.801	8.784	8.767	8.749	8.730	8.715	8.698
1.2	27.99	27.66	27.59	27.58	27.51	27.45	27.43	27.38	8.877	8.772	8.752	8.747	8.726	8.705	8.701	8.685

3. Transient analysis

Prior to setting up a transformer model suitable for transient studies, a set of test results for the commercial RWT were performed in the laboratory at FEIT. The SIMULINK model of the RWT was set up implementing the measured circuit parameters and magnetization curve as inputs. The SIMULINK model using a look-up table for the saturation is presented in Fig. 5.
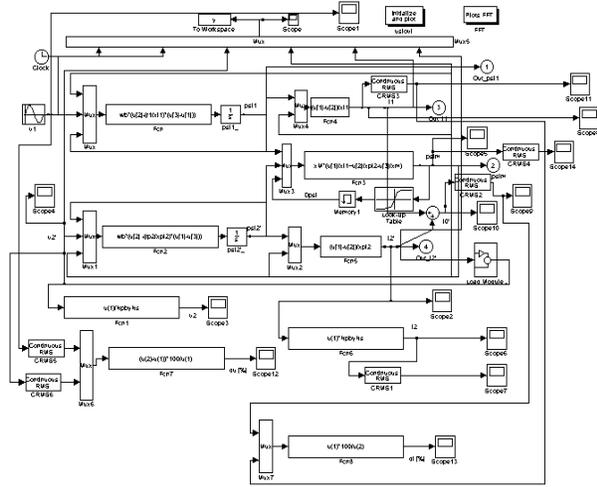

Fig. 5. Simulation model of two-winding special transformer.

The time domain transformer response is compared to actual test results, given in Table IV.

Table IV Comparison between the test and simulation results at RWT nominal position

	Test	simulation
No load rms current [A]	5,26	5,4
No load peak current [A]	/	7,5
Primary rms current [A]	125	134
Primary peak current [A]	177	187
Active core losses [W]	298	180
Reactive core losses [VA]	1529	2000

The simulation results are nearly identical to the laboratory tests. With these results the validity of the derived model has been proved. Sample results for the case of loaded RWT in steady-states is presented in Fig.6. The simulation model is also suitable for in-rush transient study of unloaded transformer that is energized at the instant when the supply voltage and residual flux are both zero. This simulation is presented in Fig. 7.
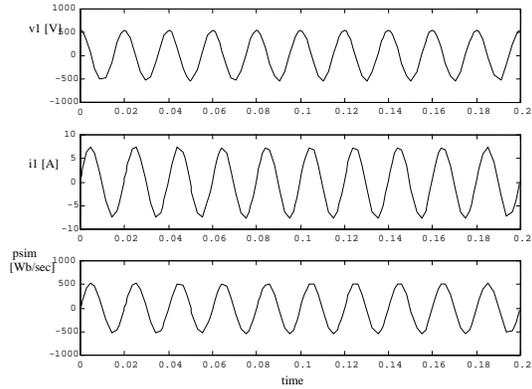

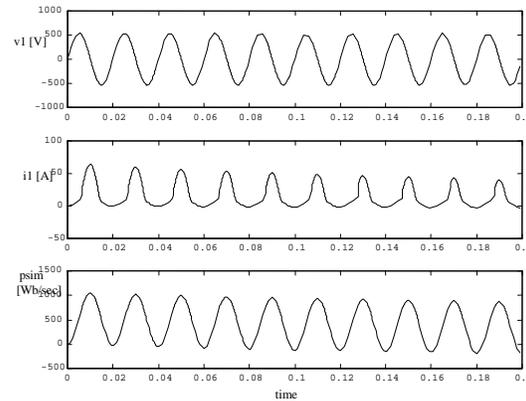*Fig. 6. Simulation – loaded RWT in steady-states*

Fig. 7. Simulation – RWT in-rush transients

With these results the validity of the derived SIMULINK model has been confirmed. The developed transformer model verified on the RWT study case is applied for transient analysis of the CCVIT. The CCVIT transient analysis is done by coupling with the above FEM-3D results. The complex non-linear analysis has been done for rated loads of the both measurement cores and rated frequency of 50 Hz. The input voltage phase angle is β=0.
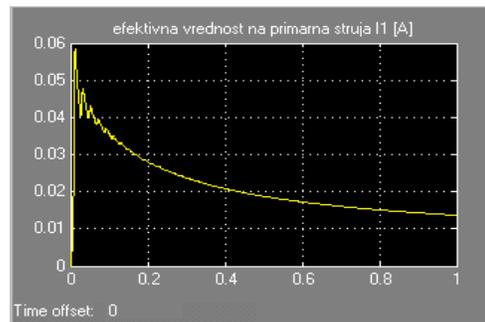

Fig. 8 Time dependence of the rms value of the primary VMC current at VMC rated load and CMC at rated regime and β=0
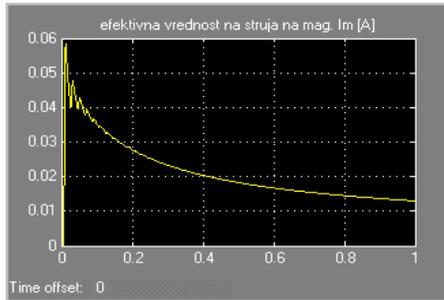
Fig. 9. Time dependence of the rms value of the VMC magnetizing current at VMC rated load and CMC at rated regime and β=0
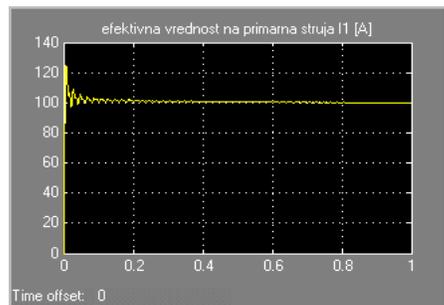

Fig. 10. Time dependence of the rms value of the primary CMC current at CMC rated load and VMC at rated regime and β=0
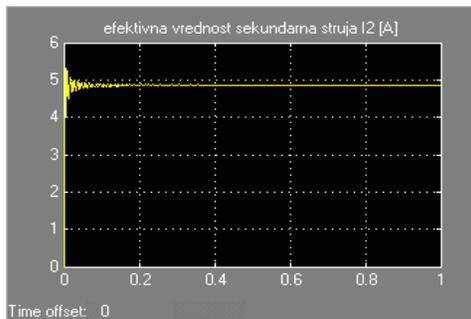

Fig. 11. Time dependence of the rms value of the CMC secondary current at CMC rated load and VMC at rated regime and β=0

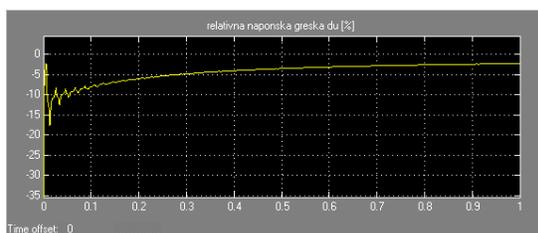In Figs. 12 and 13 the results of the CCVIT main transient metrological analysis are displayed.

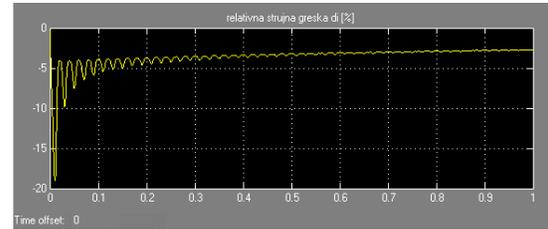*Fig. 12. Time dependence of the relative VMC voltage error p_u at rated load, CMC at rated regime and β=0.*

Fig. 13. Time dependence of the relative CMC current error p_i at rated load, VMC at rated regime and β=0.

4. Conclusions

In the paper numerical models for electromagnetic analysis of two different special transformers have been developed and experimentally verified by using the finite element method. The resistance welding transformer has been modeled by using the 2D and the combined instrument transformer has been modeled by using the 3D technique. For the both analyzed objects exact calculation of the leakage reactances has been accomplished. These FEM results have been used as an input data in the further transient analysis. The developed transient performance transformer model has been verified as accurate on the resistance welding transformer through experimental testing and it has been further applied for transient analysis of the combined instrument transformer. The confirmed transformer model has been coupled with finite element method results. The methodology in the paper is universal and can be applied for other complex electromagnetic devices.

References

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