

Experimental Verification of the CAD Analysis and Design Results of Combined Current-Voltage Instrument Transformer

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Abstract-In the paper modern CAD (computer aided design) techniques will be used for the analysis and design of a 20 kV combined current-voltage instrument transformer (CCVIT). The magnetic phenomena in the complex non-linear electromagnetic CCVIT system will be studied by using the finite element method in the three-dimensional domain and the original program package FEM-3D. The magnetic field analysis will derive the exact CCVIT metrological characteristics. The FEM-3D results are basis for further optimal CCVIT design from metrological aspect by using the stochastic method-genetic algorithm introduced in the original program as an instrument transformer design tool. The objective function during the optimization process is a combination of the CCVIT metrological parameters. Higher accuracy class will be achieved with the CCVIT optimal solution. The CAD results of the finite element method magnetic field analysis and the genetic algorithm optimal design will be experimentally verified through testing of the realized CCVIT prototype in a laboratory.

I. Introduction

The instrument transformers as one of the main measurement components in the power systems should comply with the metrological specifications of the restrictive IEC standards, [1]. The combined current-voltage instrument transformer (CCVIT) is a complex non-linear electromagnetic system consisting of two magnetic measuring cores (current measuring core CT and voltage measuring core VT) and two electrical systems as shown in Figure 1.

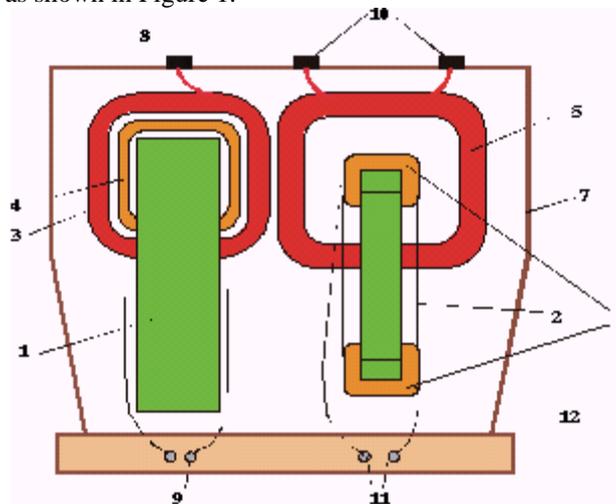


Figure 1. Electromagnetic system of the 20 kV combined instrument transformer (1-VT magnetic core; 2-CT magnetic core; 3-VT high voltage primary winding; 4-VT low voltage secondary winding; 5-CT high current primary winding; 6-CT low current secondary winding; 7-common isolation housing; 8-high voltage socket lit; 9-low voltage socket lits; 10-primary current socket lits; 11-secondary current socket lits; 12-isolation base)

As it has been previously published in [2] there is mutual magnetic influence between the two cores which influences the metrological characteristics of the transformer. The classical analytical methods for the magnetic field study can be applied only on simple electromagnetic structures which is not the case with the CCVIT. Therefore, the numerical CAD methods such as the finite element method in the

three-dimensional domain are indispensable, [2]. The main task of the study presented in this paper is to achieve a metrological optimal design of the CCVIT by using modern computer aided design techniques (CAD). The CAD analysis and design results will be verified by experimental prototype testing in a laboratory.

II. CAD Metrological Optimal Design of the Combined Instrument Transformer

A. Three-dimensional FEM-3D Magnetic Field Analysis

The magnetic field study in the three-dimensional domain of the analytically designed CCVIT begins with the system of Poisson's non-linear partial differential equations as follows:

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

where \bar{A} is the magnetic vector potential as an auxiliary quantity, \bar{B} is the magnetic flux density, $\bar{\nu}$ is the magnetic reluctivity and j is the volume current density. The CCVIT is a closed and bounded electromagnetic system with prescribed Dirichlet and Neumann boundary conditions. The non-linear iterative calculation of the magnetic field distribution in the 3D domain is achieved by using the finite element method and an original and universal program package FEM-3D developed at the Faculty of Electrical Engineering-Skopje, [3]. The program flow chart is displayed in Figure 2.

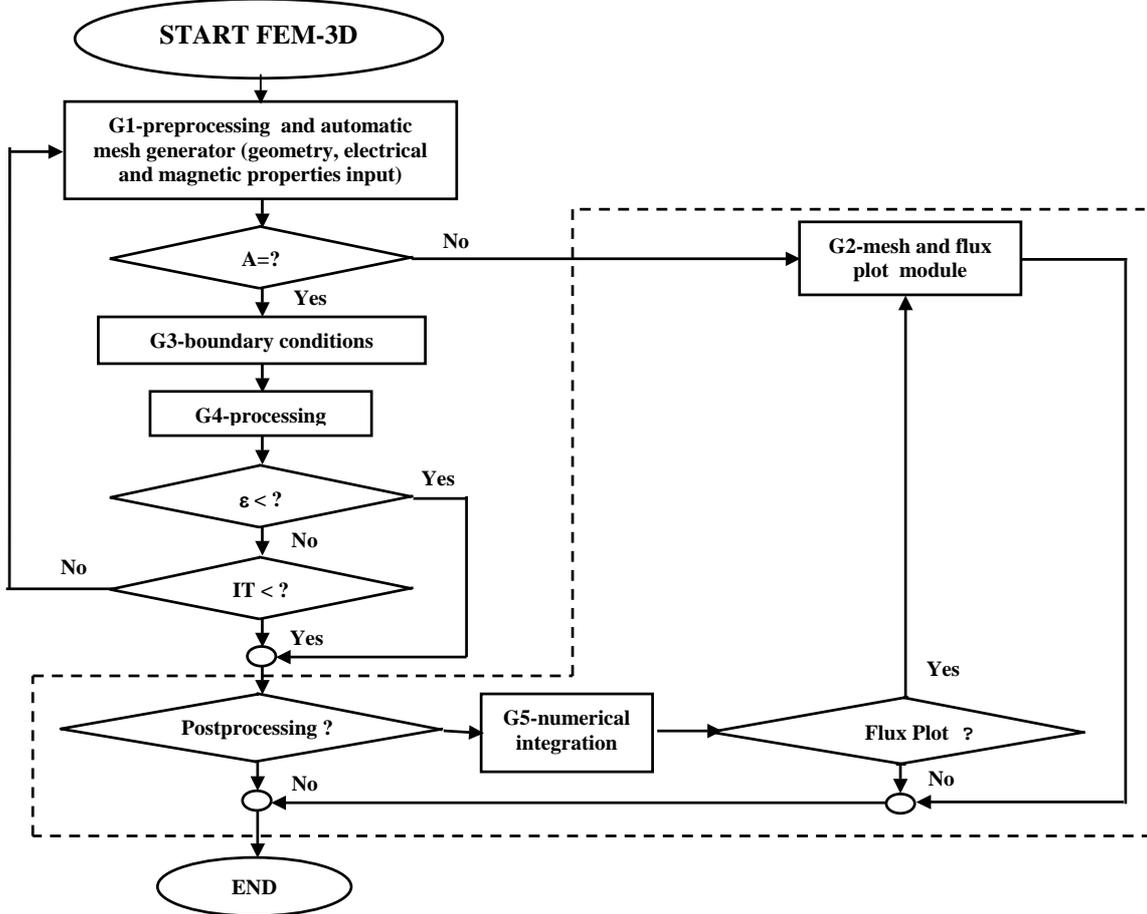


Figure 2. FEM-3D program package flow chart

The FEM-3D program package is used for calculation of the non-linear partial differential vector equation in the nodes of the 19000 finite elements of the CCVIT. For the purposes of three-dimensional modeling of the CCVIT electromagnetic system the 3D domain is divided into 19 cross-sectional layers along the z-axis, as given in [2]. The non-linearity of the two magnetic cores as well as the magnetic anisotropy and the magnetic lamination of the cores is taken into consideration by the FEM-3D program. The input primary voltage U_u (for the VT core) and the input current I_i (for the CT core) are

changed from plug out regime to 120 % of their rated values (VT rated ratio: $\frac{20000V}{\sqrt{3}} : \frac{100V}{\sqrt{3}}$ and CT rated ratio: 100 A : 5 A). The FEM-3D results for the magnetic field distribution in the CCVIT published in [2] derive the main flux and the leakage fluxes distribution. This analysis allows exact numerical calculation of the leakage reactances of the four CCVIT windings given in Figures 3-6.

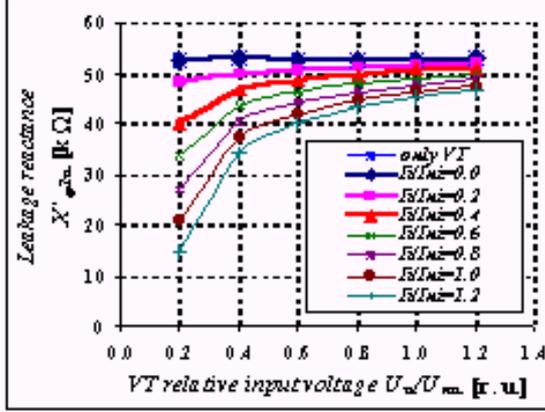


Figure 3. VT primary winding leakage reactances characteristics via the relative input VT voltage and input CT current as parameter

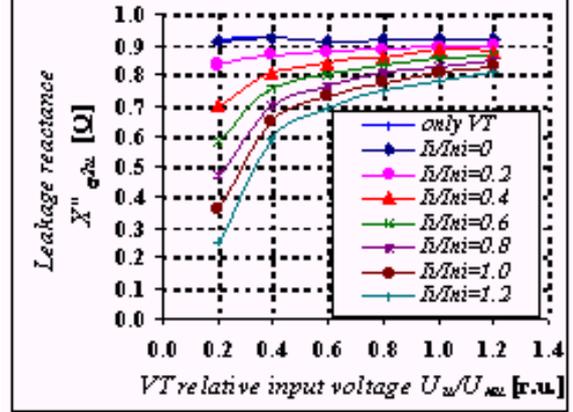


Figure 4. VT secondary winding leakage reactances characteristics via the relative input VT voltage and input CT current as parameter

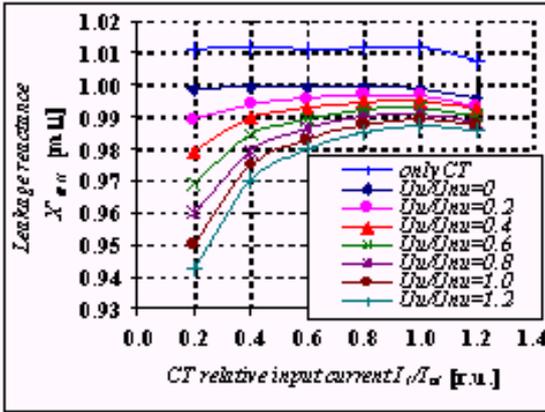


Figure 5. CT primary winding leakage reactances characteristics via the relative input CT current and input VT voltage as parameter

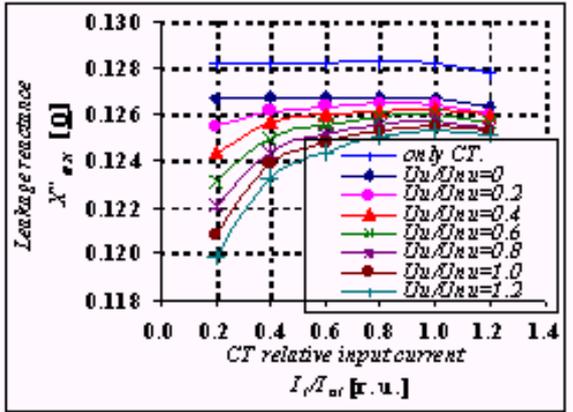


Figure 6. CT secondary winding leakage reactances characteristics via the relative input CT current and input VT voltage as parameter

B. Application of Genetic Algorithm for CCVIT Optimal Design

The FEM-3D calculated leakage reactances are input data for further CCVIT optimal design by using the stochastic design method-genetic algorithm implemented in the original program package GA, developed at the Faculty of Electrical Engineering in Skopje, [4]. The objective function in the optimization process is the minimum of the CCVIT steady state metrological parameters, the mutually coupled voltage error p_u and the current error p_i :

$$f_{opt} = \frac{1}{1 + |p_i|} + \frac{1}{1 + |p_u|} + \frac{1}{1 + |p_{u0,25}|} + \frac{1}{1 + |p_u + p_{u0,25}|} \quad (2)$$

where p_u is the VT voltage error at rated load, p_i is the CT current error at rated load, $p_{u0,25}$ is the VT voltage error at 25 % of the rated load. Through this objective function the IEC standard, [1] requirements are fulfilled. The VT and CT phase displacement errors are incorporated as boundary conditions in the GA mathematical model of the CCVIT. The rated regime for the both cores has been selected for the CCVIT metrological optimal design. In the CCVIT mathematical optimization model

all the quantities which affect the objective function are made to be dependent on 11 input optimization variables. The optimal design CCVIT project is adjusted for practical realization of a CCVIT prototype by adopting standardized geometrical and building factors which leads to the optimized design project. The optimal solution is derived by the following genetic algorithm parameters: cross-over probability 0,65; mutation probability 0,03; size of the population 16; number of generations 30000. The 11 input optimization variables, their mapping range as well the comparison of the initial, optimal and optimized values derived by the GA are given in Table 1. In Table 2. are compared the main metrological parameters, included in the GA objective function and as boundary conditions calculated in the three design projects (initial, optimal and optimized).

Table 1. Input design variables in the optimization process

design variable	mapping range		initial	optimal	optimized
number of turns of primary VT winding	23584	24000	24000	23655	23655
primary VT winding current density [A/mm ²]	1,5	3,0	2,04	1,509	1,617
secondary VT winding current density [A/mm ²]	1,5	3,0	2,61	2,000	1,677
VT magnetic core outside length [mm]	183	221	185	191,187	191
VT magnetic core depth [mm]	49	54	50	53,44	53
number of turns of secondary CT winding	115	125	120	119	119
primary CT winding current density [A/mm ²]	1,0	1,6	1,36	1,0198	1,587
secondary CT winding current density [A/mm ²]	2,0	3,0	2,55	2,495	2,548
primary CT winding copper width [mm]	9,0	11,0	10,5	9,00	9,00
CT magnetic core outside length [mm]	136	162	142	156,31	148
CT magnetic core depth [mm]	15	60	25	21,15	17,00

Table 2. Initial, optimal and optimized transformer metrological parameters

parameter	initial	optimal	optimized
voltage error at $0,25S_{nu}$ [%]	-0,752	0,775	0,771
voltage error [%] (at rated regime for both cores)	-2,42	-0,775	-0,786
current error [%] (at rated regime for both cores)	-0,68	-0,0000135	0,3154
voltage phase displacement error [min]	-74,23	-72,574	-72,402
current phase displacement error [min]	0,57	2,593	1,097

III. CCVIT Prototype Development and Experimental Verification of the CAD Results

The accurate project of the CCVIT prototype is made according to the results from the FEM-3D magnetic field analysis and the GA optimal design. The new original 20 kV combined instrument transformer prototype shown in Figure 7. is realized in the Instrument Transformer factory "EMO"-Ohrid, Macedonia.



Figure 7. 20 kV CCVIT Prototype

The prototype testing is done with high-voltage measurement set displayed in Figure 8. The high current measurements are done by the differential method. The CCVIT testing is done under simultaneous loads of the both measurement cores (voltage and current load) from plug out regime to 1,2 of the rated voltages and currents, under different loads and power factors.

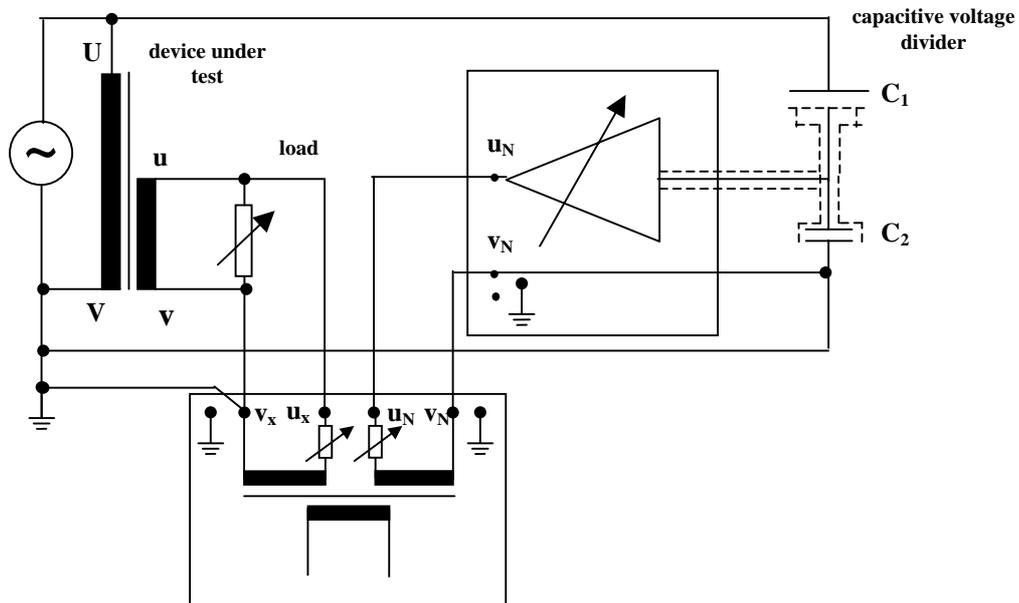


Figure 8. High voltage measurement set of the 20 kV CCVIT

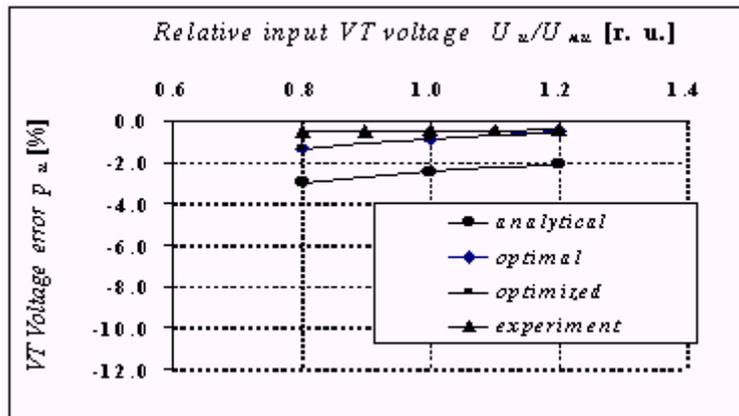


Figure 9. Comparison of the CAD and experimentally derived VT voltage error characteristics via the relative input VT voltage at rated input CT current and rated loads of the both measurement cores

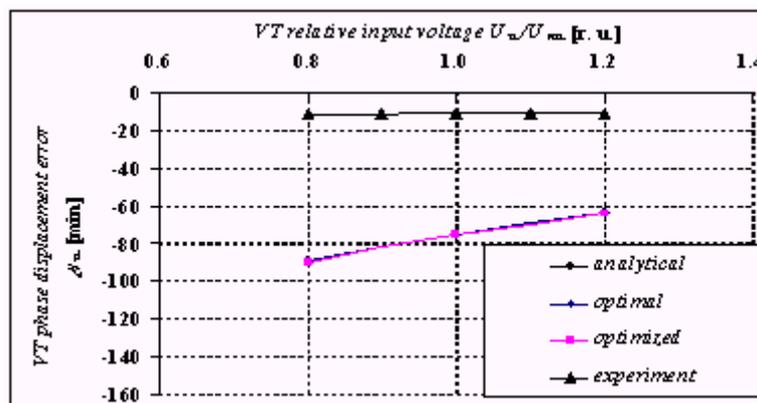


Figure 10. Comparison of the CAD and experimentally derived VT phase displacement error characteristics via the relative input VT voltage at rated input CT current and rated loads

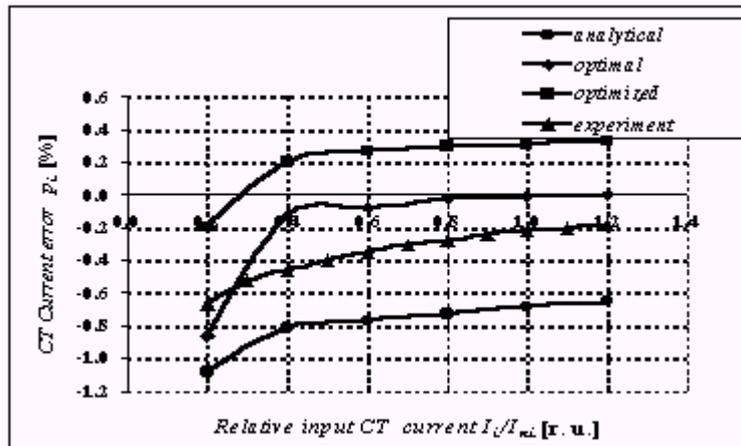


Figure 11. Comparison of the CAD and experimentally derived CT current error characteristics via the relative input CT current at rated input VT voltage and rated loads

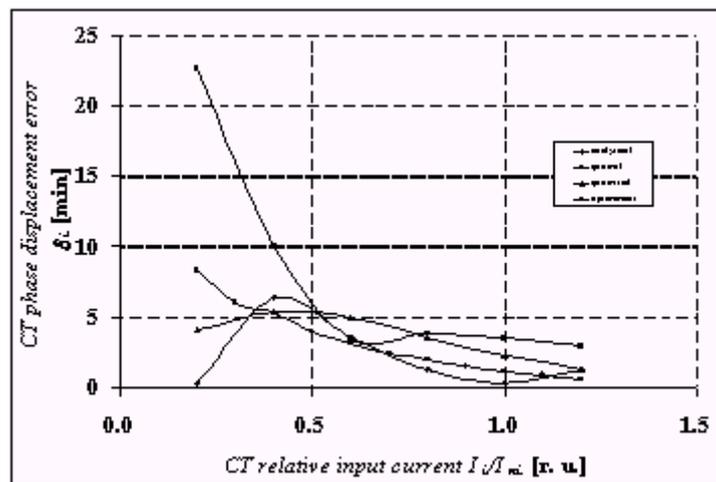


Figure 12. Comparison of the CAD and experimentally derived CT phase displacement error characteristics via the relative input CT current at rated input VT voltage and rated loads

In Figures 9-12 the main metrological characteristics (VT voltage error p_u via the input VT voltage U_u and CT current error p_i via the CT input current I_i at rated loads of the both cores) of the initial analytical, optimal and optimized CCVIT design project are compared to the experimentally derived prototype characteristics. The testing has been done according to the IEC standard specifications, [1].

IV. Conclusions

The FEM-3D analysis coupled with the GA optimal design has derived a 20 kV combined instrument transformer with improved metrological characteristics: the VT core from accuracy class 3 (analytical) has been improved to accuracy class 1 (optimal) and the CT core from accuracy class 1 (analytical) has been improved to accuracy class 0,1 (optimal). The optimized design and the prototype is with metrological parameters between the analytical and the ideal optimal CCVIT project (VT is accuracy class 1, and CT is accuracy class 0,5). The experiments have verified the positive CAD results.

References

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