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Review

Candidate: Bruno Bosnjak

Title of doctoral thesis: Short Circuit Forces and Stresses in Power Transformers

Dear Colleagues!

Attached you find my review of the PhD thesis of Dipl. Ing. Bruno Bosnjak entitled *Short Circuit Forces and Stresses in Power Transformers*.

Sincerely yours

M. Kaltenbacher

Aims and Scope

The objective of the thesis of Bruno Bosnjak is to research the short circuit conditions in power transformers applying 3D magneto-mechanical Finite Element (FE) simulations and discuss the obtained electromagnetic force and mechanical stress distribution in a real transformer. In doing so, he also performs measurements and compares measured with simulated results as well as the results obtained by standard analytical formulas.

Electric transformers are essential components in electric power supply networks and serve to transform the voltage between individual power circuits with low losses. In order to guarantee that power transformers reach their planned service life, the precise computations of thermal, dielectric and mechanical stresses are of major importance. Thereby, especially the ability of power transformers to withstand the occurring high mechanical stresses and strains at short circuits is of utmost importance to meet planned service times of up to 50 years.

Content

The thesis starts with an overview of the topic, the principle physical description of transformers and in special the occurrence of short circuits. Furthermore, the state of art of short circuit testing via IEC60075-5 is discussed, and a literature review towards the computation of electromagnetic forces and mechanical stresses due to short circuits is provided. The first chapter finishes with a clear description of the thesis objective from his performed numerical simulations to the implications for the design.

Chapter 2 describes the design of power transformers in a very understandable way. In doing so, he highlights the extremely complex structure of the core and windings (both layer and disk windings). Furthermore, he provides a good insight in the clamping of all individual components of a power transformer, which is of uttermost importance for numerical simulations (especially for the mechanical field).

Chapter 3 focuses on the short circuit duty of power transformers and describes the power transformer as a part of the whole network circuit. In doing so, he discusses simple formula for the impedance of a transformer, which in addition to the apparent network power influences the severity of the short circuit. In addition, the thermal ability to withstand a short circuit is provided and the criteria of short circuit withstand capability via testing of categories I, II and III transformers are discussed.

The fundamental relations for the computation of electromagnetic forces and its impact to the short circuit mechanical stresses calculation is dedicated to chapter 4. In doing so, Bruno Bosnjak also shows FE simulation results to demonstrate the radial and axial force distribution in the windings. Furthermore, the important topics of winding support failure, tilting, axial bending, telescoping, spiralling, hammering, compressive and tensile hoop stress as well as free and forced buckling and finally interactive failure modes are discussed and demonstrated with appealing illustrations.

Chapter 5 is dedicated to the multiphysics modelling and the FE formulation being implemented in the numerical simulation tool, which has been used by Bruno Bosnjak for all numerical computations. In doing so, he describes also his approach, which details of the transformer are considered in the numerical simulations, which parts are simplified and which are not considered. Since the fully nonlinear simulation of the coupled system is extremely time demanding, he performs also magnetically linear simulations with a relative magnetic permeability of the core of 1 and 1000. In addition, he compares static simulations with transient simulations and highlight the importance of transient simulations.

In chapter 6, he describes the mock-up transformer, the performed experiments and the comparison to the simulation results. Thereby, he was able to impressively prove that transient coupled magneto-mechanical FE simulations are necessary to obtain the more stringent criteria of dynamic maximum stresses.

Finally, the thesis closes with a summary and an outlook of further important investigations of dynamic effects in the short circuit case including the consideration of mechanical resonances, pre-stressing as well as more detailed models of the winding. Of main interest will be also the application of the developed simulation approach to foil windings.

Innovation, originality and scientific value

One can definitely say that Bruno Bosnjak performed one of the first highly precise numerical transient FE simulations solving the coupled magneto-mechanical partial differential equations in 3D to obtain electromagnetic force and mechanical stress distributions in the short circuit case. This is an enormous effort and a highly complex task, since one cannot resolve all geometric details and physical effects of a power transformer. Therefore, to build-up the knowledge, which geometric details have to be resolved (we just consider the complex structure of the core as well as the windings) and which physical effects have to be taken into account to achieve highly resolved simulation results for the electromagnetic forces and mechanical stresses in the short circuit case, is a highly notable achievement. In this sense, I can claim that the originality, innovation and scientific value of this PhD thesis is achieved. Furthermore, it should be emphasised that the numerical FE results were also compared with measurements and the standard method based on simplified analytical methods as well as FE static simulations. In doing so, Bruno Bosnjak was able to impressively prove that transient coupled magneto-mechanical FE simulations are necessary to obtain the more stringent criteria of dynamic maximum stresses. Thereby, the numerical simulation times are feasible also for everyday industrial use.

Critical remarks

At some parts the thesis would need language improvements sometimes also connected with correct description of physics. At some parts, the necessary preciseness is missing.

Examples:

- Most of the *eveloped* model assume static .. : “developed” (page 7)
- .. or time-varying directed flow of charges vector ..: well, charges flow, but charges are scalar quantities! (page 35)
- Member $e^{-t/T}$ introduces …: it is not a member, it is a mathematical term (page 36).

- Very often you reference to an equation by “Equation (1.1)” (page 4), but then you also use directly “.. according to (1.2) depends ..”! The reference to equations should be unique.
- Physically wrong: The axial forces are caused by the radial component of the magnetic flux density B and the ***axial*** forces are caused by the axial component of the magnetic density B. The bold “***axial***” should be “***radial***”! (page 39)
- Figure 4.3 has nice colours but the unit “T” for Tesla is missing!
- Figure 4.4 and Fig. 4.5: Colour bar for the forces are missing.
- Figure 4.7: Legend should be “Distribution of the axial forces along winding height of the LV winding”
- “Detailed derivation of the beam equation ***in*** can be found ..”! The “***in***” is too much. (page 53)
- “.. we can calculate the average ***axial*** force ..”! It is the “***radial***” force! (page 57)
- “.. or the middle of the parallel group where is axial component of the magnetic flux density is the highest”! To sound English: ““.. or the middle of the parallel group where the axial component of the magnetic flux density is the highest”. (page 58)
- “ .. for computational simulation of physical systems”: What is a “computational simulation”; it is a numerical computation. (page 68)
- ”toundergo”: I guess, you mean “to undergo”. (page 69)
- “.. as ***the*** fulfil the”. The “***the***” is too much! (page 70)
- “.. in Simulation 1 was ***is*** defined ..”. The “***is***” is too much! (page 77)
- “.. between the two simulations ***the*** obvious.” Instead of “***the***” you need “is”. (page (78)
- Fig. 5.7: Which colour bar is the correct one for Simulation 3: the left or right colour bar?
- Figure 5.25, left: The axis labels are much too small!

Besides this, more important are incorrect physical descriptions and formulae; standard literature is

- David J. Griffiths: Introduction to Electrodynamics (4th ed.). Cambridge University Press. ISBN 978 1 108 42041 9
- J.D. Stratton: Electromagnetic Theory. McGraw Hill, 1941

Towards incorrect physical descriptions and formulae

- Equation (1.1) is incorrect: First of all, the current is a scalar and not a vector, although we assign to a current a direction. Correct formulae

$$\vec{F} = I \int_C \mathrm{d}\vec{s} \times \vec{B}; \quad \vec{F} = \int_\Omega \vec{J} \times \vec{B} \,\mathrm{d}\Omega'$$

- Page 14: In general, we differ between hysteresis losses, eddy current losses and excess loss (includes the localised eddy current effects near the moving magnetic domain walls). So you cannot write "additional magnetic losses though the formation of eddy currents". In your wording, magnetic losses are the hysteresis losses.

- Equation (3.1): ϕ_{main} should be ϕ_{max}, since you compute it by B_{max}! You also write on page 28: .. where ϕ_{main} is the maximum magnetic flux ..".

- Page 35, after equation (4.1): when you use the winding voltage in kV, then the current also has to be in kA!

- Equation (4.7): see above

- I have no idea, how equation (4.9) can be derived?

- Equation (4.12) is wrong: The term "sin(φ)" cannot be there! You have already integrated over the angle φ, that's why you have the factor 2π. You also have to describe that the vector a_z is the unit vector pointing into the axial direction and you need a scalar product with the volume force density!

- Equation (4.13) should be a sum, because for each axial subdivision you compute a discrete value!

- Equation (4.14) is similarly wrong as (4.12)! Please not that you integrate the angle from 0 to 2π.

- Equation (4.15): Index is missing

- Figure 5.10: What do you mean with electromotive force? The correct coupling would be the motional electromotive force, which would add the term

  $$\frac{\partial \vec{u}}{\partial t} \times \nabla \times \vec{A}$$

  to (5.1), and which is implicitly taken into account, when you compute the magnetic field on the updated geometry. However, I doubt that this term is to be taken into account!

- You should clearly describe, how you perform the static analysis. You write "A static coupled magnetomechanical simulation of the transformer during a short circuit at 0.01s is set up" (page 90). You need the correct current from the transient computation and then perform with this current a static analysis!

- Equation (5.7): no description of the operator ***B***!

- All figures for the mechanical stress displays what? The mechanical stress is a symmetric tensor of second order and has therefore 6 components! I guess you display the von Mises stress, which is computed out as a scalar value from the stress tensor!

Summary
Despite the critical remarks presented above, I believe that the purpose of the dissertation is scientific and has been consistently achieved. Summing up the assessment of the PhD thesis doctoral, I state that

- the dissertation is an original solution to a scientific issue,
- Ph.D. student has demonstrated the ability to conduct research independently
- Ph.D. student has mastered general engineering knowledge in the field of the modelling and simulation of power transformers.

Given the above, I believe that the doctoral dissertation of Dipl. Ing. Bruno Bosnjak entitled "Short Circuit Forces and Stresses in Power Transformers" meets the statutory requirements for doctoral dissertations. If it is possible in your doctoral regulations, I would give Dipl. Ing. Bruno Bosnjak the opportunity to correct the errors in the formulae as well as in the English language according to the suggestions.

Finally, I am asking for the admission of the doctoral dissertation to public defence.