Coupled Electromagnetic-Mechanical Dynamic Analysis of Generator Circuit Breakers

J. Smajic[1], C. Jäger[1], S. Neubauer[2], A. Bauer[2], D. J. Cheng[2], M. Widenhorn[3]

[1]University of Applied Sciences of Eastern Switzerland (HSR), Oberseestrasse 10, Rapperswil, Switzerland, jsmajic@hsr.ch
[2]ABB Switzerland Ltd., High Current Systems, Brown-Boveri-Strasse 5, CH-8050, Zurich, Switzerland
[3]Antrova AG, Hofwisenstrasse 13, CH-8260 Stein am Rhein, Switzerland

Abstract— **Due to their specific position and role in electric power systems generator circuit breakers (GCB) must be so developed and manufactured that they can withstand extremely high short circuit currents several times over their entire life time. Therefore an accurate and efficient method for performing a coupled electromagnetic-mechanical simulation of a GCB in its full geometrical complexity is of paramount importance for daily design. This paper presents in detail a novel method for coupling of electromagnetic and dynamic mechanical analysis for GCBs. The suggested method is fast, accurate, efficient, robust and suitable for 3-D geometries of high complexity.**

Index Terms — **Circuit breakers, short circuit currents, electromagnetic modeling, numerical simulation, and magnetomechanical effects.**

I. INTRODUCTION

The voltage level of modern electric turbo-generators of the highest power (up to 1'800MW) is limited to 31.5kV for dielectric reasons. The corresponding GCB current is therefore extremely high at this voltage level. As an example, the ABB generator circuit breaker (GCB) type HEC 9 designed for largest turbo-generators is constructed to withstand a non-harmonic short circuit current with the peak value of 685kA. Consequently, the corresponding magnetic force acting on the breaker components is also extremely high which makes the mechanical breaker design very demanding.

The time dependence of the short circuit current that the breaker must withstand is precisely defined in the IEEE standard for generator circuit breakers [1]. The short circuit current is defined in terms of its RMS value, DC component, and its time constant. The typical shape of this current is depicted in Figure 1.

To develop a breaker that can withstand such extreme short circuit currents and forces and to avoid oversizing and unnecessary high material costs an efficient coupled electromagnetic-mechanical simulation method is of paramount importance.
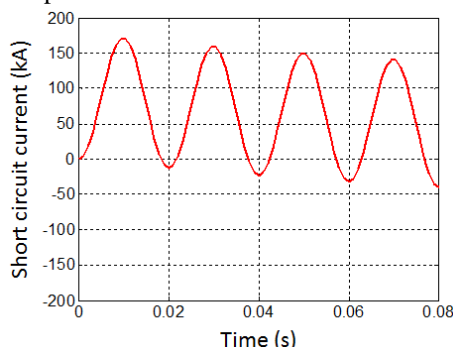

Fig. 1. Time dependence of the short circuit current with the RMS value of the AC component of 63kA according to the IEEE standard [1] is depicted.

In the existing literature there are almost no scientific papers dealing with this problematic of electromagnetic-mechanical coupling for circuit breakers. The situation is completely different in the area of electrical machines and actuators where coupled problems attracted considerable attention in the last two decades. This trend is mainly driven by industrial applications for the reason of virtual prototyping and optimization.

Already in the 1990s a solid algorithmic basis for coupled electromagnetic-mechanical analysis was established, as reported for example in [2] and [3]. In these works the so-called strong or bidirectional coupling was described, where the deformation of the structure influences the electromagnetic analysis and vice versa. The coupling channel was the electromagnetic force, the analysis was transient, and the solved examples had very simple (academic type) geometries.

Over the years thereafter emerged methods that are more suitable for industrial applications, i.e. for problems with very detailed and complicated geometry. In such cases the so-called weak or single directional coupling is usually accurate enough as the size of the simulation object is much larger than the expected deformation. Therefore, the back coupling of the mechanical analysis through the deformed shape back to the electromagnetic analysis is not necessary, as reported for example in [4] and [5]. The magnetic force is usually computed either by integrating the Maxwell stress tensor [4] and [5] (typical for electrical machines and torque calculation) or by the method of virtual work [2].

The described existing methods are not suitable for the analysis of GCBs for several reasons: (a) 3-D breaker geometry in its full complexity is almost impossible to analyze by a method that require an air box construction around the breaker components; (b) the mesh for the mechanical analysis must be the same as the mesh for the electromagnetic simulation in order to avoid the force interpolation which is too CPU-time consuming for large models. These two very practical reasons have made the application of the existing methods to the analysis of GCBs almost impossible and have led to the novel method presented in this paper.

The GCB components are very massive and made of either aluminum (busbars and other electrically conductive current carrying elements) or epoxy resin (insulators). The dimensions of the breakers are usually at least three orders of magnitude larger than the tolerable short circuit displacements. Moreover, the conductive components are so designed that the skin-effect does not radically influence the current distribution.

According to the above properties of the GCB structure the coupled analysis can be done through the following three steps: (a) an electric current distribution analysis; (b) a Biot-Savart magnetic field computation and Lorentz's force

extraction; and (c) a transient mechanical analysis based on the method of harmonic superposition.

II. METHOD DESCRIPTION AND NUMERICAL RESULTS

Due to the explained properties of the circuit breaker structure the following assumptions of the proposed method are realistic:

a. Displacements of the breaker structure due to short circuit forces are so small that they do not influence the magnetic field and force distribution (the weak or single directional coupling is sufficient).

b. Induced eddy currents do not influence significantly the distribution of short circuit forces (a static current distribution is sufficient).

c. No magnetic bodies are present in the model and the model is linear (the material properties do not depend on the field values).

The current distribution analysis of the breaker is based on the following boundary value problem:

$$\nabla(\sigma \cdot \nabla V) = 0, (x, y, z) \in \Omega \subset R^3 \tag{1}$$

$$\frac{\partial V}{\partial n} = 0, (x, y, z) \in \Gamma_L \subset R^2 \tag{2}$$

$$\frac{\partial V}{\partial n} = \frac{I}{\sigma \cdot S_I}, (x, y, z) \in \Gamma_I \subset R^2 \tag{3}$$

$$V = 0, (x, y, z) \in \Gamma_O \subset R^2 \tag{4}$$

where V is the electric scalar potential, σ is the electric conductivity of the material, Ω is the breaker volume, Γ_L is the lateral (insulating) surface of the breaker conductor, Γ_I is the input port of the breaker conductor, Γ_O is the output port of the breaker conductor, and I is the breaker current.

After the current density distribution ($\vec{J}(\vec{r})$) of the breaker is computed, the magnetic field is obtained via the well-known Biot-Savart integration:

$$\vec{B} = \frac{\mu_0}{4\pi} \iiint_{(\Omega)} \frac{\vec{J} \times \vec{r}}{r^3} \cdot dV \tag{5}$$

The force density is obtained by using Lorentz's formula:

$$\vec{f_m} = \vec{J} \times \vec{B} \tag{6}$$

The transient mechanical analysis uses the force density (6) as the load of the mechanical model. It is also important to mention that the static force density (6) must be time-modulated in each step of the mechanical analysis according to the time-shape of the square of the short circuit current given in Figure 1. This is possible because of the assumption (c) that the analysis is linear.

The transient mechanical analysis is based on the well-known dynamic equilibrium equation [6]:

$$[L]^T \cdot \{\sigma_m\} + \{f_m\} = \rho \cdot \{\ddot{U}\} \tag{7}$$

where $[L]$ is a linear operator, $\{\sigma_m\}$ is the stress tensor written in a vector form, ρ is the density of the material, and $\{\ddot{U}\}$ is the acceleration vector.

For the solution of the electromagnetic and transient mechanical problem separately the commercial solver ANSYS was used [6]. However, the described coupling method is not implemented in Ansys up to now and we have developed it

within the frame of the ANSYS Parametric Design Language (APDL) [6].

As a test case a new ABB test GCB with the nominal voltage of 24kV and the RMS value of the short circuit current of 63kA was used. Its meshed geometry is presented in Figure 2 (the breaker enclosure is hidden but modeled). The first results of the coupled electromagnetic-mechanical analysis in the form of stress distribution are shown in Figure 3.

The authors are currently working on experimental verification of the obtained results. This will be presented at the conference and in the subsequent full paper. However, it is already now possible to say that the obtained results are very plausible and in agreement with the previous experience and observations.
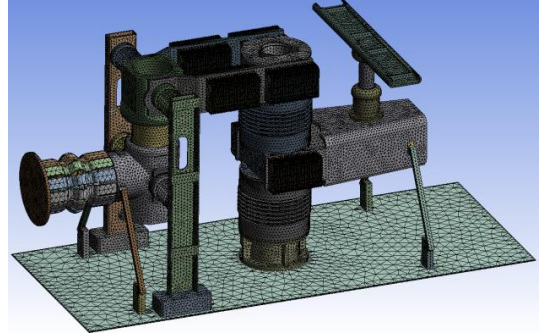

Fig. 2. The meshed geometry of one phase of the chosen ABB test GCB (24kV, 63kA) is presented. The mesh consists of 600'000 tetrahedral second order elements and 1'000'000 nodes.
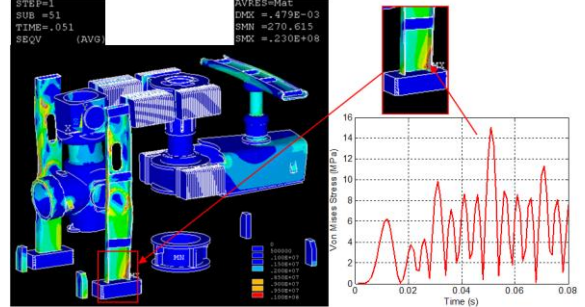

Fig. 3. The Von Mises stress distribution (left, $t=51ms$) in aluminum parts of the chosen ABB test GCB is presented. At the chosen critical place it is possible to obtain the stress over the entire fault time. The total CPU-time on a large modern multicore PC was around 12 hours.

REFERENCES

[1] "IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis", IEEE Std. C37.013-1997, The Institute of Electrical and Electronics Engineers, New York, USA, 1997.

[2] B. Gaspalou, F. Colamartino, C. Marchand, Z. Ren, "Simulation of an Electromagnetic Actuator by a Coupled Magneto-Mechanical Modeling", COMPEL – The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 14, No. 4, 1995, pp. 203-206.

[3] Y. Crutzen, S. Papadopoulos, F. V. Paemel, "Modeling, Analysis and Validation of Electromagnetic-Mechanical Coupling on Clean Test Pieces", IEEE Trans. on Magnetics, Vol. 30, No. 5, 1994, pp. 3276-3279.

[4] E. Schmidt, C. Grabner, "Application of a Weak Coupling Algorithm in the Electromagnetic-Mechanical Finite-Element Analysis for Roebel Bars of Large Synchronous Machines", IEEE Trans. on Magnetics, Vol. 41, No. 5, 2005, pp. 1896-1899.

[5] M. Furlan, A. Cernigoj, "A Coupled Electromagnetic-Mechanical-Acoustic Model of a DC Electric Motor", COMPEL – The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 22, No. 4, 2003, pp. 1155-1165.

[6] ANSYS 14.5, Ansys Inc., www.ansys.com, Canonsburg, PA, 2012.