Transient Coupled Electromagnetic-Mechanical Simulation of Generator Circuit Breaker

Jasmin Smajic, Michael Conry

ABB Switzerlan Ltd., Corporate Research
Segelhofstrasse 1K, CH-5405 Baden 5. Dättwil, Switzerland

Summary

The algorithm for coupled transient electromagnetic-mechanical analysis is presented here in details. For comparison, the commercial software tools ANSYS, and ABAQUS have been used along with the in-house developed tool - POLOPT. Although the considered field coupling is rather clear from the theoretical viewpoint, it is very difficult to solve this problem on a real-life geometry of generator circuit breaker. Since severe difficulties regarding modeling, meshing and numerical computations have been encountered, it was necessary to verify the obtained results. Therefore, we have developed two independent simulation chains. The first algorithm has been realized by using ANSYS Classics for modeling and ANSYS Workbench for geometry handling and meshing. The second algorithm has been developed by using our in-house written BEM based electromagnetic solver POLOPT and mechanical solver ABAQUS. The obtained results have been compared for a simplified and real-life breaker geometries.

Keywords

Generator circuit breaker, electromagnetic analysis, stationary current distribution, mechanical analysis, harmonic superposition algorithm, transient analysis

1. Introduction

The transient electromagnetic-mechanical simulation of a generator circuit breaker (GCB) is an important and necessary step in the design. Within the life-time of the breaker a short circuit in its vicinity, as the most stressful failure from the mechanical viewpoint, is supposed to occur several times. Therefore the used equipment, i.e. the breaker parts has to sustain an enormous mechanical stress produced by the short circuit current. Concerning a GCB in general, the short circuit current is strictly defined by the standard IEEE Std C37.013-1997 [1]. The standard defines the short circuit current including its DC component, the time-constant of its exponential decay and its duration according to the expected opening time of GCB contacts.

Having a significant exponentially decaying DC component the short circuit current produces an electromagnetic field that is not time-harmonic and therefore the transient analysis is needed. It is worth mentioning here that the time-variation of the short circuit current can be represented as a harmonic expansion using the Fourier's theory. Thus, the complete analysis can theoretically be done in a frequency domain. However, as it is explained in Section 2 such a harmonic superposition at the level of electromagnetic field computation is not needed for linear materials involved. If eddy-currents are neglected, it is enough to perform a sequence of 6 different current distribution (CD) analyses (DC Laplace's problem) to obtain sufficient input for the subsequent transient mechanical analysis. Therefore we have chosen not to do the harmonic superposition at the level of electromagnetic analysis, but to perform a stationary CD analysis followed by a transient mechanical analysis. In our opinion this approach is simpler, more effective (CPU time, memory) and can be, as such, easier accepted by designers.

The transient short circuit current is defined in such a way that it reflects the worst possible short-circuit scenario from the GCB viewpoint. Thus its electromagnetic field produces enormous electrodynamic force acting on the mechanical structure of the breaker. Without an accurate prediction of the force and corresponding stress, the components of the GCB have to be oversized to make sure that they will sustain the short circuit current test and possible fault currents in their life-time. Therefore we are of the opinion that such a transient electromagnetic-mechanical analysis can be very helpful in the design phase of the GCB to improve/optimize existing and develop new breakers.

The paper is organized as follows. The algorithm is described and tested on a simplified geometry in Secton 2. The real-life breaker geometry has been anlyzed and results have been presented in Section 3. Section 4 concludes the paper.

2. Algorithm for Coupled Transient Electromagnetic-Mechanical Analysis

The model used in the simulation is based on the following simplifying assumptions:

1. the eddy-current effect is not significant (although the exact numbers regarding the influence of eddy-currents are currently not known at the moment, this effect is supposed to be not so significant, and will be analyzed in future in detail);
2. the corresponding deformations of the structure are small enough that the linear elasticity can be assumed;
3. the corresponding deformations of the structure are very small compared to its dimensions; thus the influence of the deformations on the electromagnetic field computation is negligible and no equilibrium-locked loop (the recursive cycle of the electromagnetic and mechanical analysis in which the deformation as an output of mechanics goes back to electromagnetics and so on, until the equilibrium is reached) is needed.

In order to test the algorithm and accuracy of the results the simplified model of the generator circuit breaker has been defined and shown in Figure 1. As one can see, the geometry is so simple that a regular mesh can be used, as shown in Figure 2. Thus, highly accurate solutions with relatively small number of degrees of freedom (DOFs) will be obtained which is appropriate for the subsequent numerical tests and comparisons.

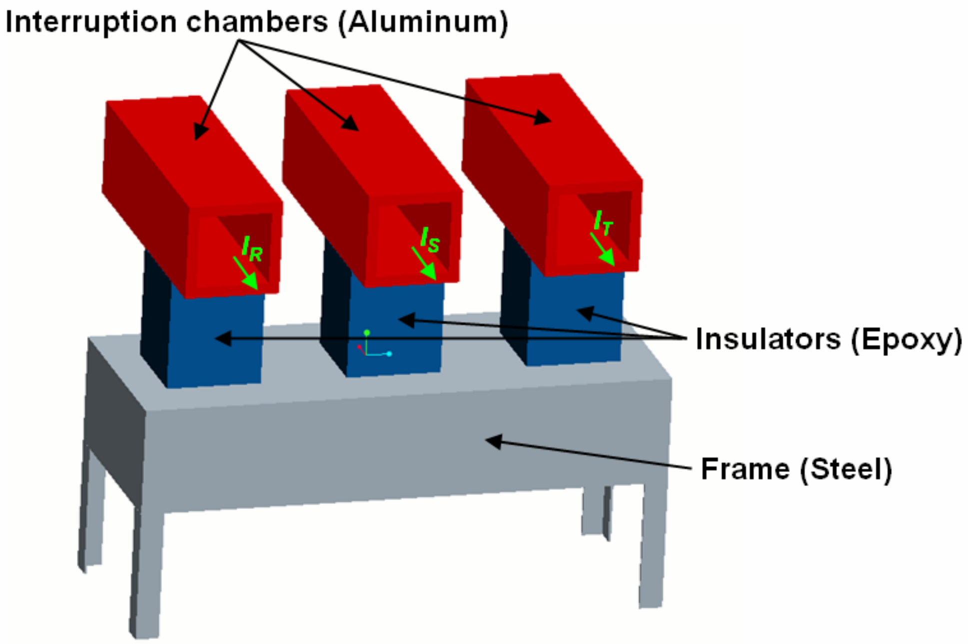


Figure 1. The simplified model of GCB is shown; the three interruption chambers (aluminum) supported by the three insulators (epoxy) are mounted on the frame (steel); through the chambers is flowing the three phase system of currents (I_R, I_S, I_T).

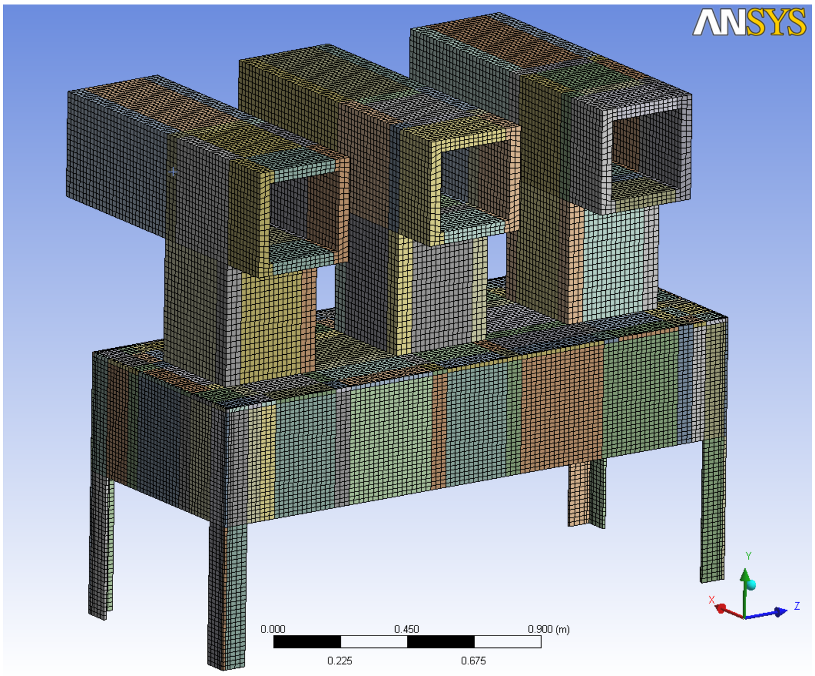


Figure 2. The Workbench mesh of the simplified model of the GCB is shown; the mesh consists of 57439 hexahedrons and 324184 nodes; such a regular mesh guaranties a high level of accuracy for the subsequent numerical tests.

As we can see in Figure 1, the three phase system of short-circuit currents flow through the chambers. Since we neglect the effect of eddy-currents (Assumption 1), and since our system is linear from the mechanical point of view (Assumption 2) we can significantly simplify the electromagnetic part of our analysis. Namely, instead of having a transient electromagnetic analysis we can compute the stationary current distribution (DC) in the chambers for a unit electric current (1A), calculate the corresponding magnetic field by using the Biot-Savart law [2], and at the end compute the corresponding electromagnetic force density. The force density as an outcome of the electromagnetic analysis will be modulated and used as a load for the transient mechanical analysis.

It is now important to explain the approach of converting a static force produced by the magnetostatic analysis into a dynamic load needed for the transient mechanical analysis. Let us consider first the three-phase system of short circuit currents described by the IEEE standard [1]:

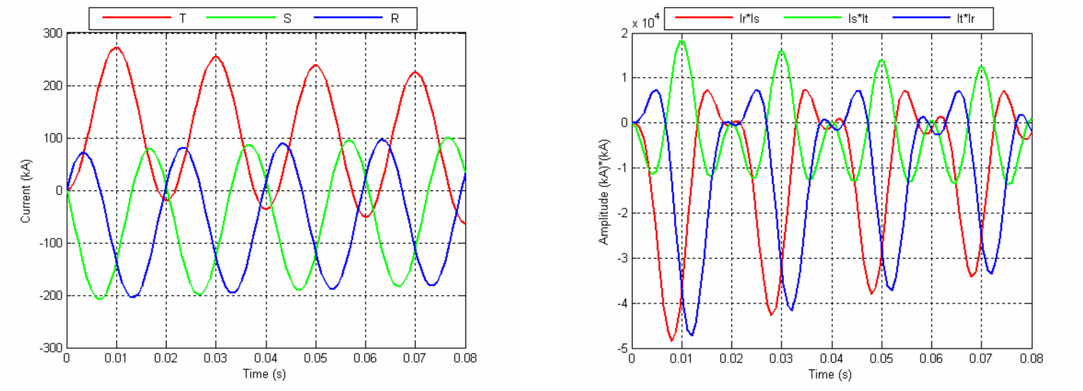
$$i_R(t) = \sqrt{2} \cdot I_{EFF} \cdot \left[\sin\left(\omega t - \frac{\pi}{2} \right) + e^{-\frac{t}{\tau}} \right] \tag{1}$$

$$i_S(t) = \sqrt{2} \cdot I_{EFF} \cdot \left[\sin\left(\omega t - \frac{\pi}{2} - \frac{2\pi}{3} \right) - \sin\left(-\frac{\pi}{2} - \frac{2\pi}{3} \right) \cdot e^{-\frac{t}{\tau}} \right] \tag{2}$$

$$i_T(t) = \sqrt{2} \cdot I_{EFF} \cdot \left[\sin\left(\omega t - \frac{\pi}{2} - \frac{2\pi}{3} \right) - \sin\left(-\frac{\pi}{2} - \frac{4\pi}{3} \right) \cdot e^{-\frac{t}{\tau}} \right] \tag{3}$$

Where I_{EFF} is the effective value of a stationary (after transient) short-circuit current, and τ is the time constant of the electric circuit.

The system of currents (1)-(3) is shown in Figure 3a. The idea of converting a static load into a dynamic one is based on the superposition principle which can be used here as long as the linearity assumption 2 is valid. Namely, on the electromagnetic side we compute the static interactions between the phases for currents of 1A. Taking into account the symmetry, we need to compute 6 different magnetostatic cases with the corresponding force densities denoted as f_{12}, f_{13}, f_{23}, f_{11}, f_{22}, f_{33}.



(a) (b)

Figure 3. The first 4 cycles of the short circuit phase currents (by following the standard IEEE Std C37.013-1997) are shown (a); The corresponding amplitudes, i.e. the modulation factors which will be used in transient ANSYS mechanical analysis are depicted as well (b).

The force densities f_{12}, f_{13}, f_{23} represent mutual magnetic interaction between the phases, and f_{11}, f_{22}, f_{33} are force densities describing the magnetic effect of each chamber on itself. Having such interactions produced by the current of 1A, it is straightforward to modulate them by the following force factors computed for the short-circuit currents (1)-(3):

$$a_{11}(t) = i_R(t) \cdot i_R(t) \tag{4}$$

$$a_{22}(t) = i_S(t) \cdot i_S(t) \tag{5}$$

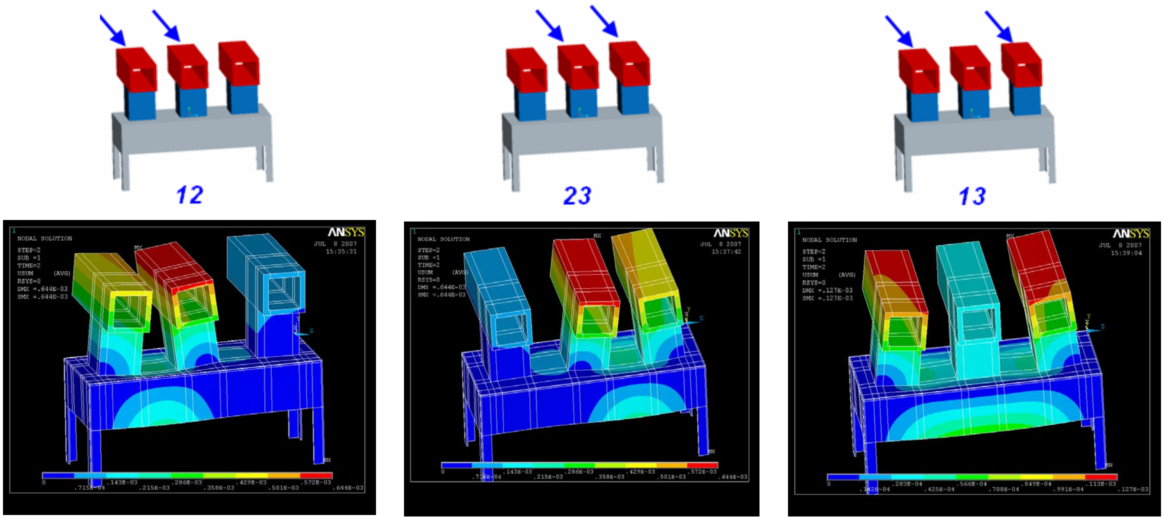
$$a_{33}(t) = i_T(t) \cdot i_T(t) \tag{6}$$

$$a_{12}(t) = i_R(t) \cdot i_S(t) \tag{7}$$

$$a_{23}(t) = i_S(t) \cdot i_T(t) \tag{8}$$

$$a_{31}(t) = i_T(t) \cdot i_R(t) \tag{9}$$

The force modulation factors (4) – (9) are shown in Figure 3b.
The force densities f_{11}, f_{22}, f_{33} represent the self influence of the magnetostatic field and force deforming the shape of the conductor itself while f_{12}, f_{13}, f_{23} describe the interactions between the phases. More about the meaning of the mutual interactions f_{12}, f_{13}, f_{23} can be seen in Figure 4.



(a) (b) (c)

Figure 4. The mutual interactions represented by the force densities f_{12} (a), f_{23} (b), and f_{13} (c) are shown; the coresponding static deformations are depicted as well.

After the force densities f_{11}, f_{22}, f_{33}, f_{12}, f_{13}, f_{23} are computed, they can be modulated by using the modulation factors (4) – (9) and used as a load of transient mechanical analysis at each time step. According to the standard [1] and estimated reaction time of the breaker, the time interval of our transient mechanical analysis is chosen to be 4 cycles of the short-circuit current, i.e. 80ms as the period is 20ms (50Hz). Besides the time interval, it is necessary to choose the time step for transient analysis. The time step will determine the duration of the calculation, its stability and accuracy [3]. As a compromise between the accuracy (sampling resolution) and CPU time, the time step of 1ms has been chosen for all the transient simulations presented in this paper.
By following [3] for ANSYS transient dynamic mechanical analysis three different methods are available: full implicit method, modal superposition method, and reduced method. Since our analysis does not involve nonlinearities, we have chosen the modal superposition method as it is faster and more efficient for our problem [3].
The first step of the dynamic transient analysis based on the modal superposition is the eigenvalue analysis of the breaker structure. In order to test the numerical technology of ANSYS for eigenvalues extraction we have performed the eigenvalue analysis of the breaker shown in Figure 1 using both ANSYS and ABAQUS mechanical solvers and compared the results. This comparison is given in Table 1. As one can see the agreement of these two solvers was very good, although we could not maintain an identical mesh, as we have used different mesh generators (ANSYS Workbench 11.0 and CADfix 7.0).
A very important question related to the mode-superpostion transient analysis is how many modes we should take into account for a given geometry and load. To determine this number, we have used a serial of numerical tests in which the displacement at a certain point of the

Table 1 The comparisson of the results of eigenvalue analysis performed on the breaker given in Figure 1 by using ANSYS and ABAQUS; the first 50 eigenvalues have been extracted; CPU time for both solvers was around 30 minutes, for a similar mesh density (Figure 2).

Mode	ANSYS, f(Hz)	ABAQUS, f(Hz)
1	22.131	21.893
2	22.409	22.062
3	26.294	25.902
4	28.102	27.641
5	29.44	28.888
6	30.32	29.744
7	47.722	47.683
8	51.596	52.748
9	59.788	61.334
10	67.15	66.395
11	68.043	68.911
12	70.005	69.846
13	72.925	74.892
14	79.059	80.332
15	81.954	80.588
16	90.59	89.497
17	96.7	98.071
18	105.93	108.21
19	109.9	110.42
20	119.93	121.25
21	137.49	130.05
22	139.93	131.91
23	144.57	144.86
24	153.38	155.41

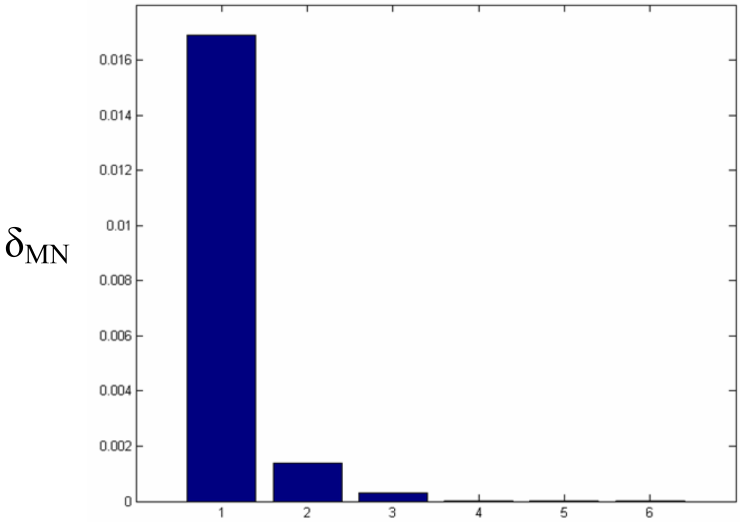
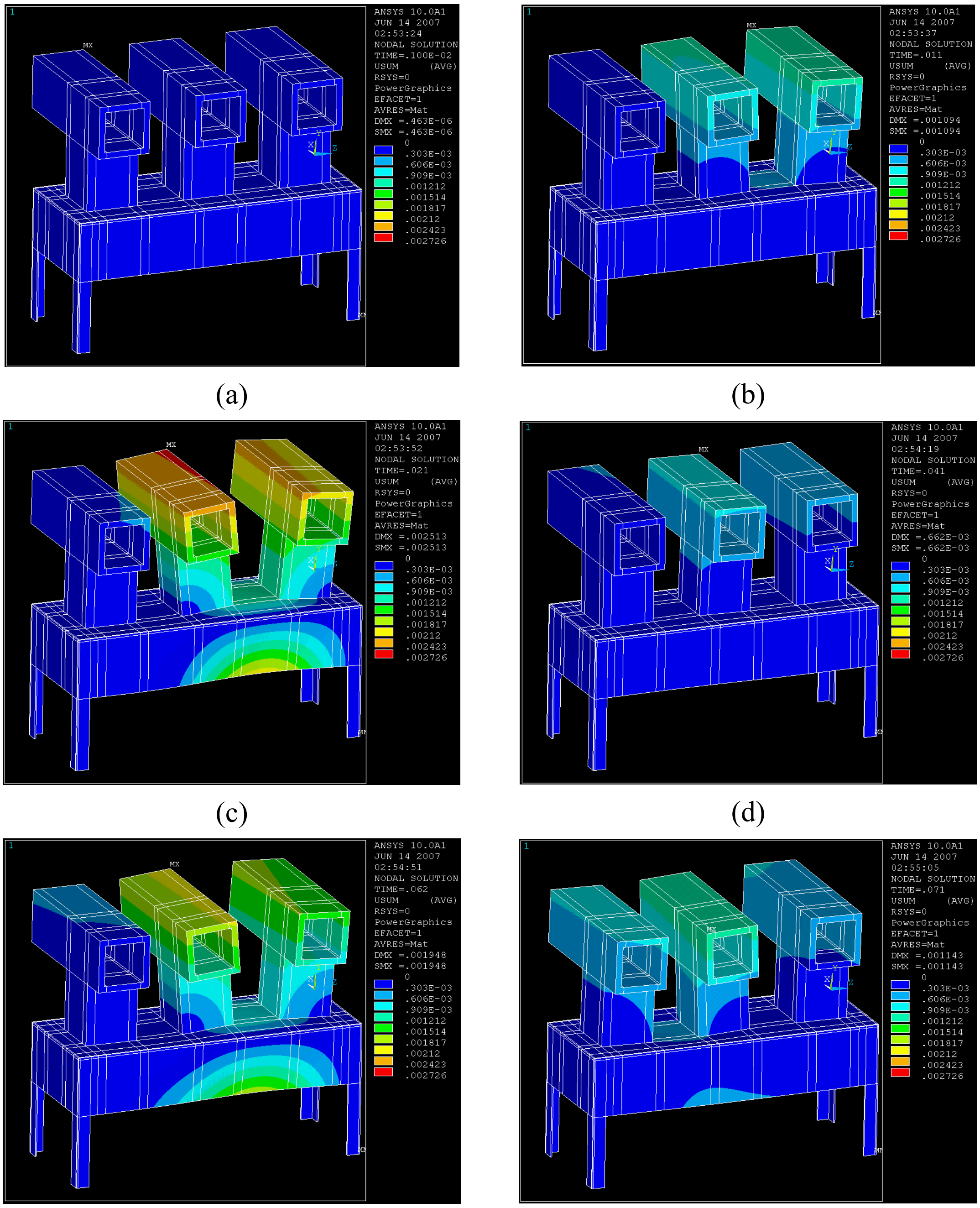


Figure 5. The analysis of the number of modes needed for an accurate transient simulation based on the modal superposition; the meaning of the x axis is related to the equation (20) as follows: M=10,N=5 (1), M=20,N=10 (2), M=30,N=20 (3), M=40,N=30 (4), M=50,N=40 (5), and M=60,N=50 (6).



(a) (b)

(c) (d)

(e) (f)

Figure 6. The results of the ANSYS transient mechanical analysis in a form of displacement are presented at the following moments of time: 1ms (a), 11ms (b), 21ms (c), 41ms (d), 62ms (e), and 71ms (f); a sequence of such results is very suitable to generate a movie.

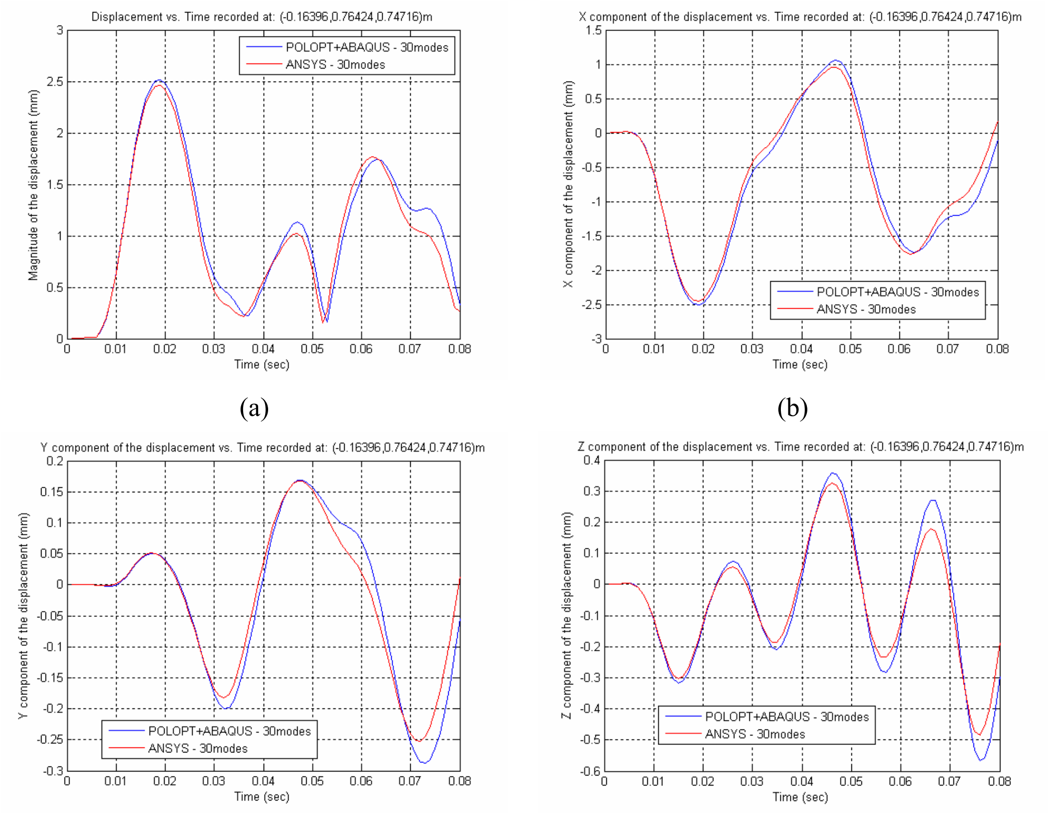
breaker during the transient analysis is recorded. These tests are repeated for different number of modes taken into account and the following error integral has been computed:

$$\delta_{MN} = \frac{\int_0^{4T} \left| u_M(\vec{r},t) - u_N(\vec{r},t) \right| \cdot dt}{\int_0^{4T} \left| u_N(\vec{r},t) \right| \cdot dt}, M > N \qquad (10)$$

Where $\vec{r}$ is the position vector of a certain point on the breaker, $u(\vec{r},t)$ is the displacement at this point at the moment *t* of time, and *M*, *N* are the number of modes taken for mode-superposition. A typical result of such an analysis for the breaker given in Figure 1 is shown in Figure 5.

As one can see in Figure 5, it makes no sense to take more than 40 modes for the subsequent transient analysis based on the modal superposition. Similar analysis has been performed for all the examples presented in the paper.

Based on the eigenvalue analysis the mode-superposition transient analysis of the breaker shown in Figure 1 has been performed with the transient loads produced by modulating the force densities f_{11}, f_{22}, f_{33}, f_{12}, f_{13}, f_{23} with factors (4) – (9). The displacements of the structure at several moments of time, as a result of the ANSYS transient mechanical analysis are presented in Figure 6.



(a) (b)

(c) (d)

Figure 7. The result comparisons between ANSYS and POLOPT + ABAQUS transient mechanical analysis; the displacement at a certain point of middle phase is recorded and its magnitude (a), x- (b), y- (c), and z-component (d) are compared; apparently the exelent agreement between different solvers is obtained.

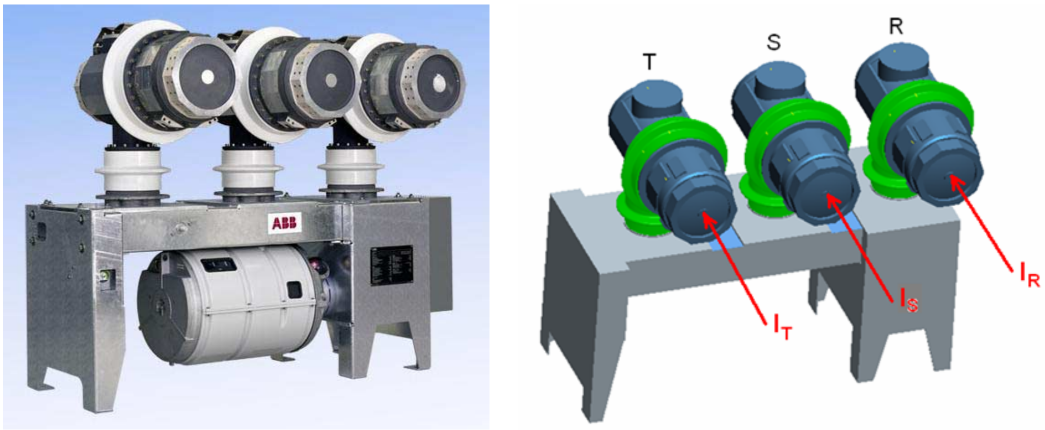
The same transient analysis has been repeated by using our BEM based in-house developed electromagnetic simulation tool POLOPT and mechanical solver ABAQUS. In both simulations the displacement an the top of middle interruption chamber is recorded and compared. This comparison is shown in Figure 7.

As one can see in Figure 7, an excellent agreement between solvers is obtained. This result is very promising, although it has been obtained for a relatively simple geometry and high quality of the mesh. Therefore in the next section the same analysis is repeated for a real-life geometry of the breaker.

3. Real-life model of GCB

Let us consider the design of the so-called Retrofit generator circuit breaker presented in Figure 8a. This solution is aimed at older power plants which were initially planed and built up without a generator circuit breaker (GCB) between the generator and the block-transformer.

The simplified geometry used for simulation has been constructed out of the original CAD drawings from the factory. This is given in Figure 8b.



(a) (b)

Figure 8. The “Retrofit” GCB Type HECS-100R/130R (a) along with the corresponding simulation model (b) is shown; the dimensions of the breaker are W=1120mm, H=1885mm, L=2700mm, its short circuit breaking current is 100kA (HECS-100R) and 130kA (HECS-130R) and the rated continuous current is 9kA (for both HECS-100R and HECS-130R).

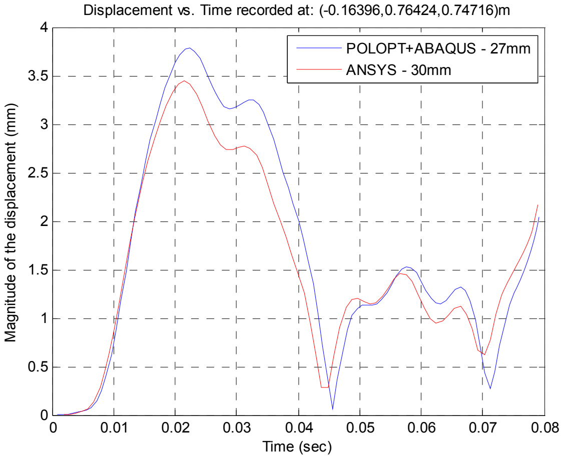


Figure 9. The result comparison for transient electromagnetic-mechanical analysis of “Retrofit” GCB Type HECS-100R/130R between ANSYS and POLOPT+ABAQUS approach is shown; the same time step (1ms), number of modes (50), and mesh size (tetrahedron side of around 30mm) have been used; the dissagreement of less than 10% has been detected.

As one can see in Figure 8b the breaker geometry is rather complicated and a regular hexahedral mesh can not be used. A tetrahedral mesh has been used instead and the same mesh density has been set for both ANSYS and POLOPT+ABAQUS calculations. After the complete already described simulation chain for transient coupled electromagnetic-mechanical analysis of the breaker has been performed, the displacement at a certain point of the middle chamber is recorded and compared. The comparison is presented in Figure 9.

Apparently, agreement between two different solvers presented in Figure 9 was also very good, as the error of less than 10% has been detected. This shows that our algorithm works well and gives a reliable result even in the case of complicated real-life geometry.

4. Conclusions

The algorithm for tree-phase coupled transient electromagnetic-mechanical analysis has been presented in detail. Two different electromagnetic and mechanical solvers ANSYS and POLOPT+ABAQUS have been used and the obtained results have been compared. The accuracy in the case of simplified model was excelent and for the real-life breaker very good as the error of less than 10% has been detected.

5. References

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