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Influence of a metallic wall on 245 kV disconnector behaviour during short-circuit test

J. A. Güemes[1], A. M. Iraolagoitia[1] and P. Fernández[2]

[1] Department of Electrical Engineering
[2] Department of Electronic Technology

E.U.I.T.I., University of the Basque Country UPV/EHU
Rafael Moreno Pichichi 3, 48013 Bilbao (Spain)
Phone/Fax number: +0034 946 014363 / +0034 946 014300
e-mail: joseantonio.guemes@ehu.es, ana.iraolagotia@ehu.es, pablo.fernandezr@ehu.es

Abstract. When testing electrical devices, it is not always possible to provide locals with dimensions large enough to guarantee that metallic elements (walls or other elements) not essential for the test, are located far enough to ensure that they will not affect the distribution of the electric or magnetic field, or forces that may appear during testing of the devices.

Some questions to be answered are: a) test results are distorted by presence of these metallic elements? b) if so, to what degree are influenced? and c) how could we quantify its value without building new laboratories, and raising economic cost?

The main objective of this paper is to analyse influence of a metallic wall on behaviour of a 245 kV disconnector during short-circuit test developed in laboratory and, compare electrodynamic force on disconnector when the test is carried out with and without metallic wall. Behaviour simulation of disconnector is carried out using finite element method (FEM). Force is calculated using Lorenz force method. Results show that calculated force is strongly dependent on model size and element size.

Key words

Alternating current disconnector, electrodynamic forces, finite element method.

1. Introduction

It is easy to determine magnetic flux density surrounding a long straight wire carrying a current I and also forces between two parallel wires of infinite length carrying currents I_1 and I_2.

Indeed, supposed two parallel straight conductors (see Fig. 1) carrying currents I_1 and I_2, both conductors generate a magnetic field, creating attractive forces if current direction is the same and repulsive force when are opposite.

The current in wire 1 produces a magnetic field density B_1 at the location of wire 2 which can be calculated by Biot-Savart law [1].

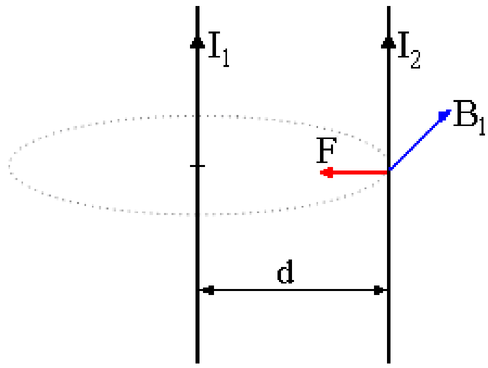


Fig. 1. Force between parallel currents.

$$B_1 = \mu \frac{I_1}{2\pi d} \qquad (1)$$

where μ is the environment magnetic permeability and d is the distance between conductors.

This magnetic flux density imposes on a segment of l length of conductor 2, carrying a current I_2 a force which module is [2]:

$$F = \mu \frac{I_1 I_2 l}{2\pi d} \qquad (2)$$

Is common practice to develop tests for electric devices at which:

- path of electric conductors required for the testing and carrying huge currents cannot be considered to be parallel of infinite length, and

- metallic parts near conductors are capable of modifying magnetic flux density distribution and so, of distorting test results.

In these cases, calculation of electrodynamic force between conductors is not easy and simulation techniques are required. One of those techniques is FEM.

The main objective of this paper is to determine influence of a metallic wall on a 245 kV, 3150 A, 50 Hz alternate current disconnector during short-circuit test in laboratory Modelling and calculation is developed by 3D-model FEM simulation.

2. Short-circuit test description of disconnector

Disconnector under test is of 245 kV rated voltage and 40 kA short-circuit current. Testing for these devices is described in UNE-EN 62271-102 [3].

Electric circuit utilized for disconnector test is showed in Fig. 2. Room problems in laboratory has made compulsory for C3 and C4 conductors to pass through a wall built up of metallic plate 1.5 mm thick.

Fig. 2. Electric circuit of disconnector.

It can be observed that:

- circuit made up of conductors C1 (flexible), C2 (flexible), C3 (rigid) and C4 (rigid), and the disconnector is arranged in U shape (see Fig. 2 and Fig. 3). In this paper, we will refer to C3 conductor as "bridge";

- disconnector is placed at horizontal direction perpendicular to metallic wall and at 5,2 m above the ground;

- C2 conductor goes through opening of a gate at metallic wall and at 0.2 m below lintel. During laboratory test, gate is open. For FE modeling, the gate is considered to be closed.

- C4 conductor crosses metallic wall through a hole on it.

Length of any conductor, separation between parallel conductors and distance from disconnector and metallic wall are shown in Fig. 3. Disconnector is 2.5 m long.

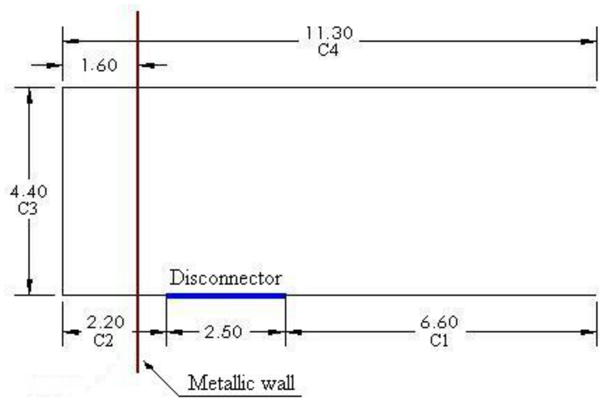


Fig. 3. Distances.

3. Simulation

Simulation is carried out using FE technique, considering surrounding air as a solid material of constant magnetic permeability.

For force calculation, time-harmonic magnetic analysis (also called AC magnetic) belonging to the low-frequency electromagnetic domain are realized.

Maxwell's equations relevant to AC magnetic analysis fields are:

$$\nabla \mathrm{x}\, \boldsymbol{E} = -\, \mathrm{j}w\, \boldsymbol{B} \tag{3}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{4}$$

where $\boldsymbol{E}$ is the electric field and $\boldsymbol{B}$ is the magnetic flux density.

On the other hand, $\boldsymbol{E}$ is related to current density ($\boldsymbol{J}$) and electrical conductivity (σ) by the expression:

$$\boldsymbol{J} = \sigma\, \boldsymbol{E} \tag{5}$$

A very important quantity that is to be considered when developing AC magnetic study is skin depth (δ). The skin depth gives an indication about the penetration of the magnetic field in the conducting regions. It can be calculated by:

$$\delta = \frac{1}{\sqrt{\pi\, \mu\, \sigma\, f}} \tag{6}$$

where f is the frequency.

It is clear that penetration of magnetic field is lower when frequency increases.

Calculation of δ is relevant mainly due to two reasons:

- a) It gives us an indicator of whether the problem must be treated with AC magnetic analysis or as magnetostatic analysis. The rule for this decision is: if the ratio of the thickness of the conductor to the skin depth in that conductor is less than one, then the problem can be treated as a magnetostatic problem. On the contrary, if the ratio is larger or equal to one, then the problem must be treated with AC magnetic analysis (we can still use the AC magnetic even if ratio < 1; the opposite is not true.

- b) It gives an indication of how must be the mesh inside a conductor. In the first skin depth penetration from the surface of the conductor, the mesh must have at least two elements per skin depth**.**

For industrial frequency of 50 Hz and copper conductor surrounded by air, skin depth is:

$$\delta = \frac{1}{\sqrt{\pi\, \mu\, \sigma\, f}} = 9.3\,\mathrm{mm} \tag{7}$$

Electromagnetic forces can be calculated by some of the following:

- The Lorentz force method;
- The virtual work method;
- The Maxwell stress method;

All of them are very sensitive to mesh size.

The Lorentz method is very useful for finding forces acting on conductors. This is the method used in this paper for calculation of the force on the disconnector.

The Lorentz force can be calculated by [4]:

$$F = I \int_l d\, \boldsymbol{l}\ \mathrm{x}\ \boldsymbol{B} = \int_v (\boldsymbol{J}\ \mathrm{x}\ \boldsymbol{B})\, dv \tag{8}$$

where v is conductor volume.

For AC magnetic analysis both $\boldsymbol{J}$ and $\boldsymbol{B}$ are complex quantities and are time dependent. In this case we calculate the time-average force by means of the following expression:

$$F = \frac{1}{2} \int \mathrm{Real}\left(\boldsymbol{J}\ \mathrm{x}\ \boldsymbol{B}^*\right) dv \tag{9}$$

A. FE model

Model is made up of four conductors (C1 to C4) indicated above, disconnector, wall and surrounding air.

Conductors (C1 to C4) and disconnector are considered of round section of 50 mm diameter and arranged on a horizontal plane (see Fig. 4) at 5.2 m above ground.

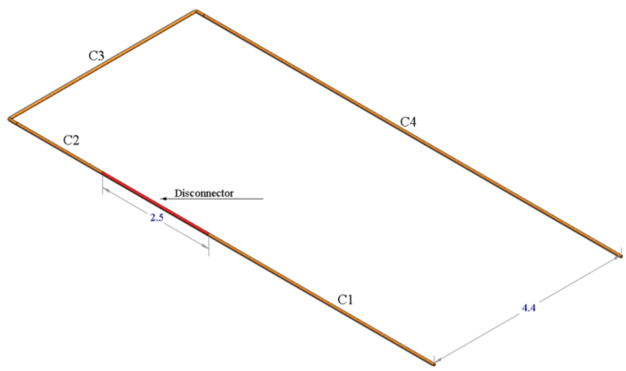


Fig. 4. Electric circuit.

Metallic wall sizes are shown in Fig. 5. Wall thickness is 1.5 mm.

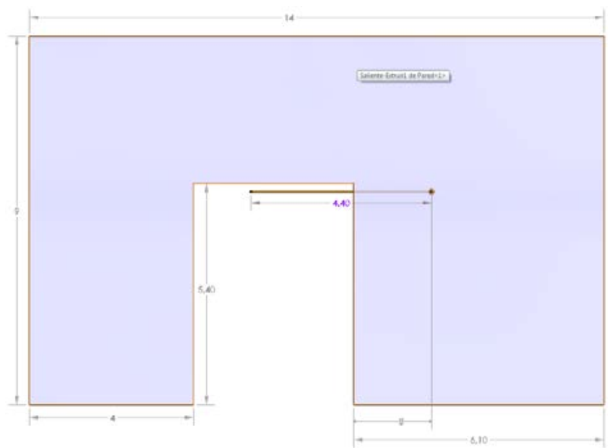


Fig. 5. Metallic wall.

Air volume used is shown in Fig. 6. As a result, we can consider that minimum distance from centre of each conductor to edge of air "box" is 9 m (far enough to admit that magnetic flux density is negligible at that distance).

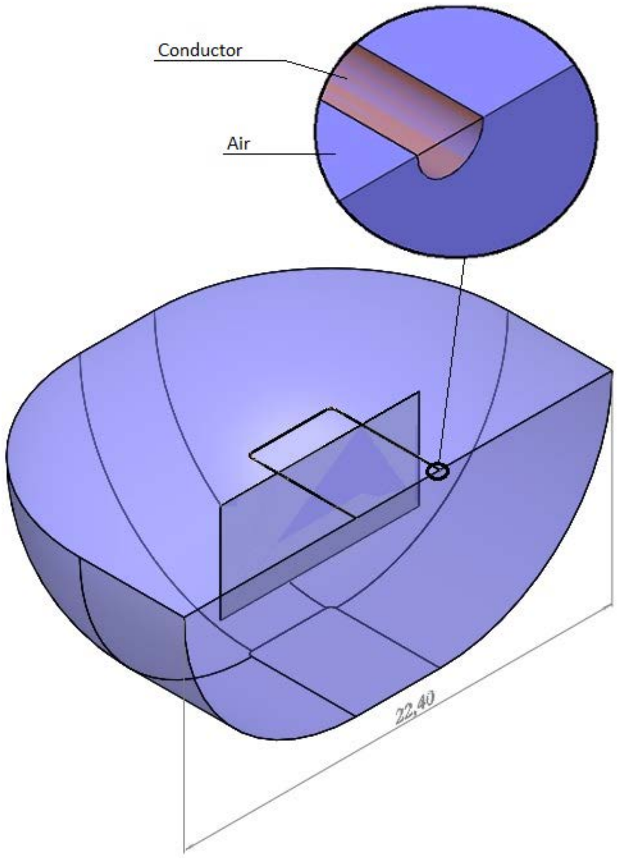


Fig. 6. Model.

We can see that magnetic symmetry is used; all conductors, disconnector and wall are cut by a horizontal plane at 5.2 m above ground. The boundary condition in all surfaces of this plane is normal flux (see Fig. 7).

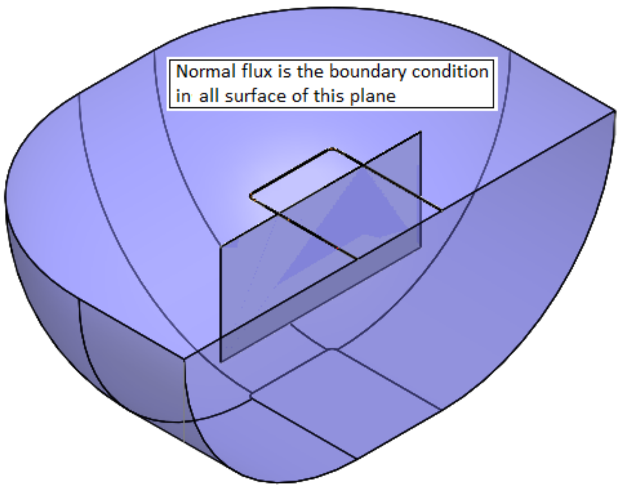


Fig. 7. Boundary condition.

B. *Analysed models*

Three models are analysed. Solid volumes are the same at each model; only magnetic properties of the solids are changed. Thus, the mesh is unique for all models and errors due to different mesh type are eliminated when model simulation results are compared.

1) Model A

Only parallel conductors, carrying a 40 kA current in opposite direction, are considered (see Fig. 8), C3 conductor is considered with the same magnetic property than air. The wall is not considered in this model.

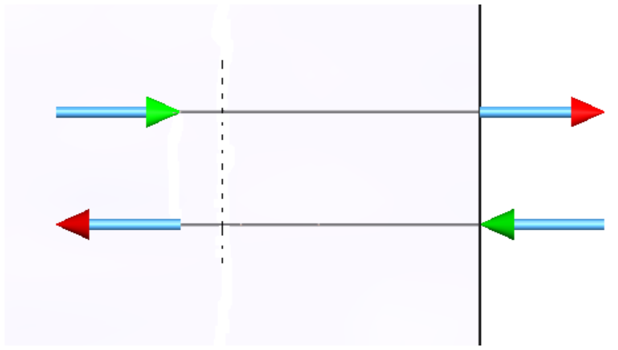


Fig. 8. Parallel currents.

This analysis tries to verify if force obtained on disconnector is similar to that calculated by means of equation (2). This simulation is very important, as it will allow us to adjust size and transition of FE mesh.

Results give a computed force on disconnector of 183.68 N, while calculation by expression (2) is 181.8 N. We can see that results are very similar.

2) Model B

All conductors and disconnector are considered carrying a 40 kA current. The wall is not considered in this model (see Fig. 9).

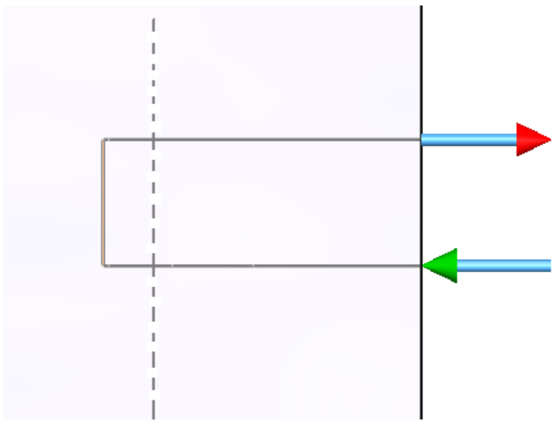


Fig. 9. Conductors and disconnector.

This model intends to assess influence of "bridge" (C3 conductor) only surrounded by air, comparing force calculated on disconnector in this model and in A model.

The analysis shows that force on disconnector is of 183.69 N. By comparing to force obtained in A model, is clear that influence of bridge (C3 conductor) on force on disconnector is minimum. Given wall position relative to bridge and disconnector, we can assume that influence of metallic wall on force acting on disconnector (during tests) can be neglected.

3) Model C

All conductors, disconnector (carrying a 40 kA current) and metallic wall are considered. This model relates to real arrangement of all elements during short-circuit test. For analysis, linearity between magnetic flux density and magnetic field for material of the metallic wall is assumed. A relative permeability of 100 is considered.

Analysis verifies influence of metallic wall, on disconnector behaviour, by comparison of this model with B model.

Developed analysis gives a force on disconnector of 172.82 N. We can observe that force on disconnector is reduced in 10.8 N (183.69 – 172.82), which means a decrease of 5.98 %.

Difference in force value indicated above is clearly incorrect, as analyzing again this model (with the same mesh), but assigning to the metallic wall the magnetic property of air, the computed force on the disconnector is 179, 52 N. That is, real decrease of the force is only of 6.7 N (179.52 – 172.82), equivalent to a 3.73 %. The difference of 172.82 N calculated in the new analysis comparing to results obtained in the model without wall (183.69 N in B model) is due to errors caused by mesh transition (the difference between the two models is simply to introduce a new body - the wall with magnetic property of air - with a very small thickness).

From these results it can be concluded that, for disconnector position and distance to metallic wall, there is no significant variation of forces on disconnector when test is performed with and without metallic wall.

Figure 11 shows real and imaginary components, at the instant when ωt = 0, of magnetic flux density for A, B and C models, along a 1 m line with origin at the centre of disconnector, perpendicular to it and on a plane located at 5.2 m above ground (points A (0, 0, -0.5) to B (0, 0, 0.5) showed in Fig. 10).

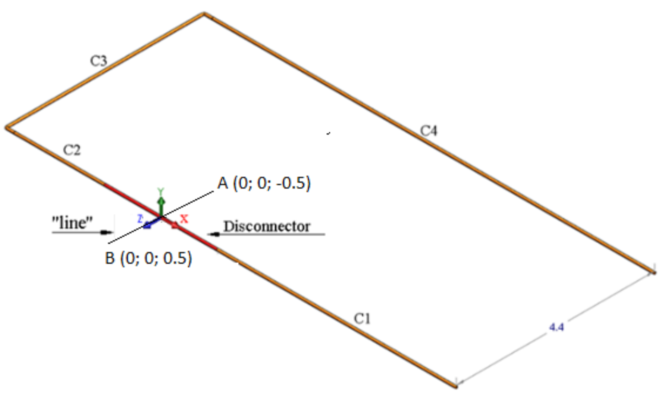
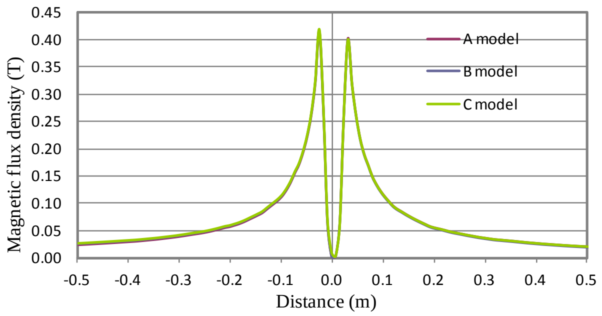
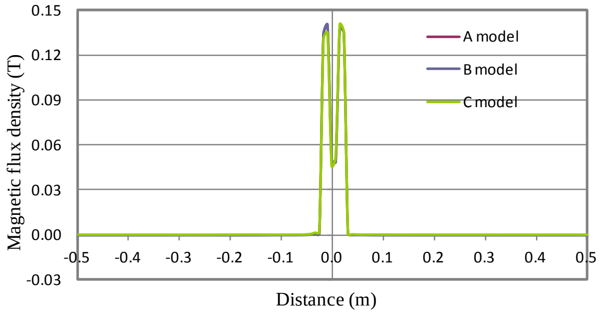


Fig. 10. Magnetic flux density.



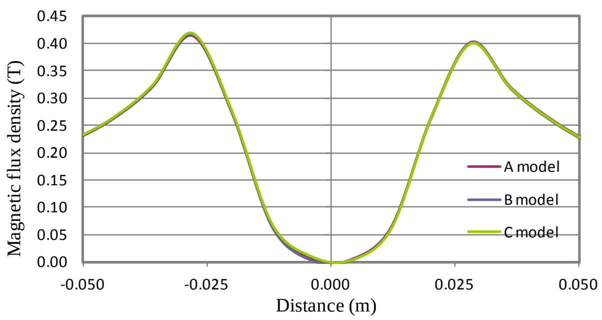
b) Real component.



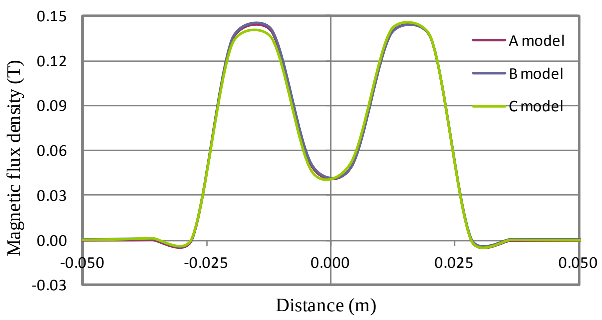
b) Imaginary component.

Fig. 11. Magnetic flux density.

Figure 12 shows with more detail Fig. 11 for distances between - 0.05 and 0.05 m (take notice that disconnector is simulated as a cylindrical conductor of 0.025 m radius)



a) Real component.



b) Imaginary component.

Fig. 12. Magnetic flux density.

Above mentioned results show that significant differences are not appreciated in magnetic flux density along measurement line; nevertheless maximum magnetic flux density obtained at other areas is higher in C model compared to results obtained in A and B models.

4. Effect of distance between wall and disconnector

In this section, we consider possible effect of distance to metallic wall from disconnector.

Table I shows calculated force on disconnector for distances between wall and disconnector from 0.3 and 1.8 m. In every model the position of disconnector is unchanged and conductor configuration is supposed to be the same of C model. Simulation is developed for two cases: a) wall is assigned relative permeability of air and b) wall is given a relative permeability of 100.

Calculation of force, when the wall is assigned magnetic property of air, aims to determine errors induced by mesh transition (different for every model even if we use the same mesh controls and element growth rate). For every model the same value of 183.69 N should be obtained.

Table I. Forces on disconnector.

Distance	F_a (N)	e_{mt}	F_b (N)	F_d (N)	e_a	e_r %
0.3	177.24	- 6.45	171.11	177.56	-6.13	- 3.33
0.6	179.52	- 4.17	172.82	176.99	-6.70	- 3.65
0.9	182.77	- 0.92	175.30	176.22	-7.47	- 4.06
1.2	183.85	+ 0.16	177.66	177.50	-6.19	- 3.36
1.5	182.51	- 1.18	179.26	180.44	-3.25	-1.76
1.8	183.68	- 0.01	180.40	180.41	-3.28	-1.78

In this table, F_a is the force calculated when the wall is assigned magnetic properties of air; e_{mt} is the error due to different meshing (F_a – 183,69); F_b is the force obtained when metallic wall is assigned a relative permeability of 100; F_d is the force computed with metallic wall in the model (F_b) when mesh transition errors are corrected (F_b – e_{mt}); e_a and e_r are absolute and relative differences of the force on the disconnector caused by metallic wall (e_a = 183.69 – F_a and e_r % = 100 * e_a / 183.69).

From these results it can be concluded that there is no significant variation of electrodynamic force (relative error is always smaller than 5 %).

5. Conclusions

For disconnector position and distance to metallic wall, there is no significant variation of forces on disconnector when test is performed with and without metallic wall.

Results show that calculated force is strongly dependent on model size, elements size and mesh transition

The bridge of electrical circuit (current flowing perpendicular to disconnector) has no effect in force on the disconnector.

Metallic wall has the effect of reducing length of parallel conductors.

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