Tutorial: calculating field stress on a high-voltage insulator with HiPhi

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1 Introduction

My assignment was to determine electric field levels along the bushing of a high-voltage circuit breaker as a function of nearby structures. Figure 1 shows the assembly. A flashover was observed on the upper section of bushing (marked A). The hypothesis was that the proximity of the grounded structure supporting the disconnect switch (marked B) resulted in field enhancement on the bushing. If this were the case, it could be beneficial to increase the height of the switch support.

I used the **HiPhi** code for the study. I calculated the electric field variation along the top of the bushing for several configurations:

- The *ideal* bushing with no surrounding structures.
- The original geometry shown in Fig. 1.
- The full system with the disconnect switch assembly raised 2.1 m.
- The original system with the grounded support of the disconnect switch removed.
- The original system with a larger grading structure on the top of the bushing.

I reached the following conclusions. First, the fields were considerably higher on the ideal insulator with all surrounding structures removed. The rods connecting the breaker to the switch increased the effective size of the top electrode, reducing the field at the top of the bushing. Second, the difference in field resulting from removal of the grounded beam or elevation of the switch assembly was negligible compared to the strong variation of field magnitude along the bushing. Finally, a larger top electrode gave a significant reduction in the electric field along the top of the bushing.

2 Model

At the time I was given the assignment, I received only the photograph of Fig. 1 and several benchmark dimensions. I constructed a three-dimensional mesh by taking scaled measurements from the photograph. Although the resulting mesh is not a precise replica of the system, it is close enough to make relative comparisons. I employed several other simplifications to limit the calculation time to about 15 minutes:

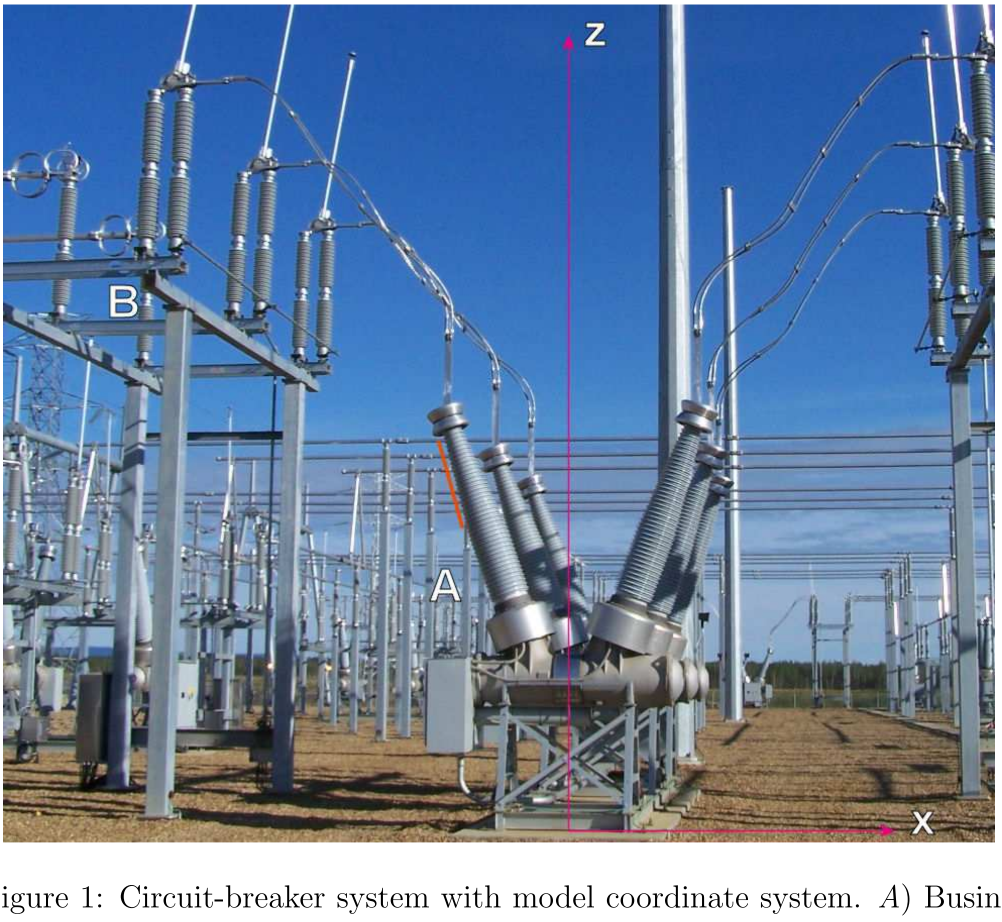

Figure 1: Circuit-breaker system with model coordinate system. *A*) Busing (height 2.7 m). *B*) Grounded base of the disconnect switch. Orange line shows the path for electric field scans.

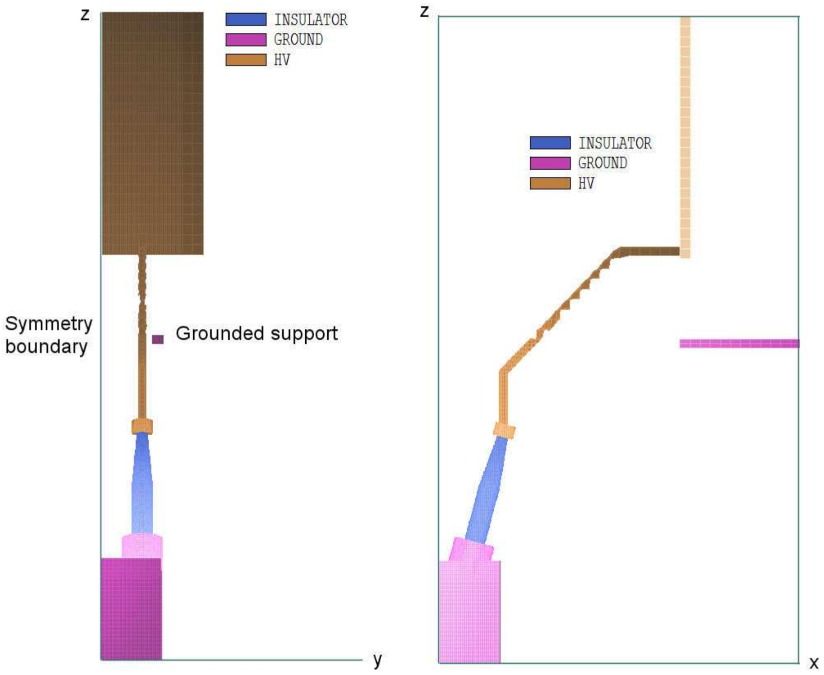

Figure 2: Three-dimensional mesh representation of the system, views from the $+x$ and $+y$ directions.

- I did not include convolutions on the surface of the bushing.
- I modeled only the region $x < 0.0$ m, with a mirror symmetry boundary at $x = 0.0$ m to represent the two sides of the circuit breaker. The solution volume extended to $x = -9.0$ to minimize the effect of the lower boundary in x.
- In y direction, I applied a symmetry boundary at $y = -1.0$ m to represent an array of circuit breakers spaced 2.0 m apart. The solution volume extended to $y = 8.0m$ to approximate the free-space condition.
- In z direction, the bottom of the solution volume at $z = 0.0$ m was a ground plane. All components in the upper part of solution were biased to the high-voltage, so I set the upper boundary to the fixed-potential condition $\phi = V_0$.
- I did not model details of the top of the switch assembly and extension rods. Instead, I represented the sum of the parts as a thin plate at $\phi = V_0$ extending to the top boundary.

Figure 2 shows the completed mesh with 785,536 elements. I employed fine element resolution around the circuit breaker and coarser resolution in peripheral regions to speed the calculation. Although the top part of the connecting rod was not perfectly resolved, the gaps had a negligible effect on field levels at the bushing. The regions labeled *Ground* had $\phi = 0.0$V, while the *HV* parts were at potential $\phi = 1.0$V to create a normalized solution. To determine operational field levels, the reported values should be multiplied by the working voltage. I used $\epsilon_r = 5.0$ for the bushing dielectric, a typical value for ceramics. All input files are included in a zip archive supplied with this report. Those with the suffix `MIN` define mesh geometries, while those with suffix `HIN` control the electrostatic calculations. The file `CNRL.SCR` controls automatic field scans for the five cases studied.

One issue is that there is a proprietary field-grading system internal to the Toshiba bushing. Because I have no knowledge of this structure, my only option was to model the bushing as a homogeneous insulator between the end caps. Note that the internal grading structure could significantly affect the actual field variation.

3 Results

There are several ways to view three-dimensional field solutions – I have included two. Figure 3 shows contours of electrostatic potential in the plane $y = 0.0$ m for the existing assembly. Air elements are shown in light blue and the switch bushing dielectric in light red. Figure 4 shows a three-dimensional view of the surfaces of the circuit breaker support, the bushing electrodes, the bushing dielectric and the bottom of the connecting rod for the existing assembly. The surfaces are color coded according to the value of $|\mathbf{E}|$.

In Fig. 3, note that the connecting rod has a large effect on the field distribution near the top breaker electrode. It increases the effective size of the electrode and the isolates the bushing from the effect of the grounded support beam (visible near near the bottom). The result is that the presence of the switch assembly actually reduces the electric field level on the insulator. For comparison, Fig. 5 shows the electric field distribution for the ideal case where the switch assembly and connecting rod have been removed. The top breaker electrode is biased to 1.0 V. The field is highly concentrated near the electrode. The orange line marked *Ideal* in Fig. 6 shows the variation of $|\mathbf{E}|$ along the scan line of Fig. 1. The peak field is reduced by adding the existing switch structure (Fig. 4 and the blue line of Fig. 6).

The field variation that results from raising the switch assembly 2.1 m is indistinguishable from that of the existing system in Fig. 6. Figure 7 shows the difference in field levels. The plotted quantity is the field in the raised system minus that of the existing system divided by the field in the raised system. The result is that raising the switch would slightly increase the field on the top of the bushing. The increase distance to the grounded

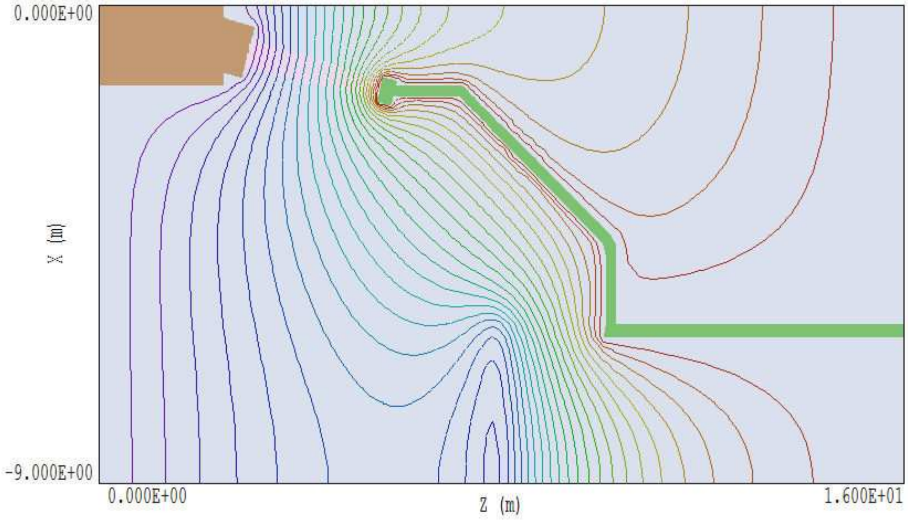

Figure 3: Equipotential contour lines in the plane $y = 0.0$ m for the existing assembly.

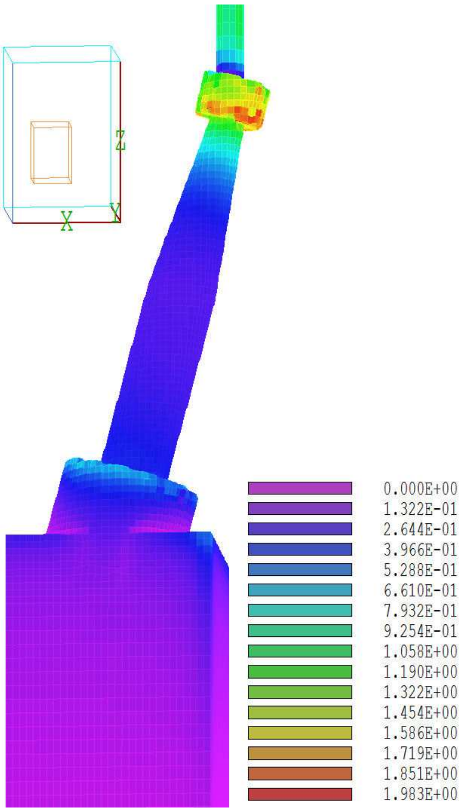

Figure 4: Three-dimensional view of object surfaces color-coded according to the normalized electric field magnitude $|\mathbf{E}|$.

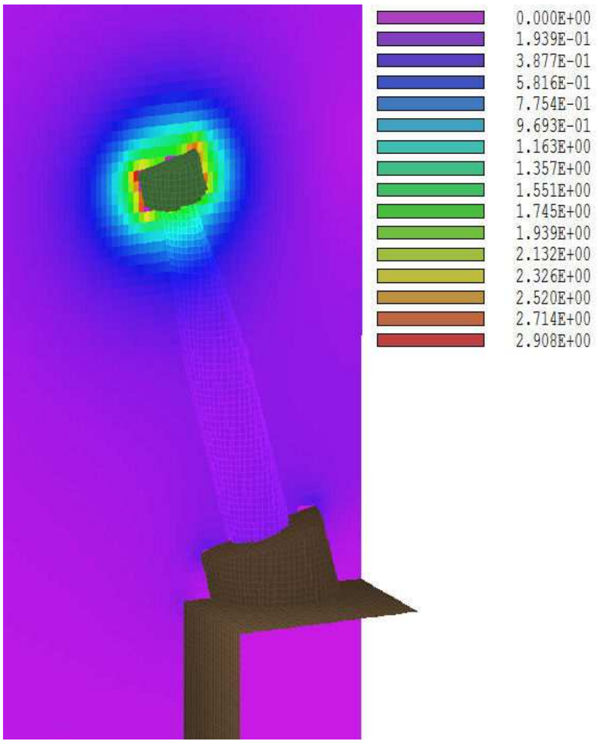

Figure 5: Three-dimensional view showing $|\mathbf{E}|$ in the plane $y = 0.0$ m and on the surface of the breaker bushing for the *ideal* case with the switch assembly removed.

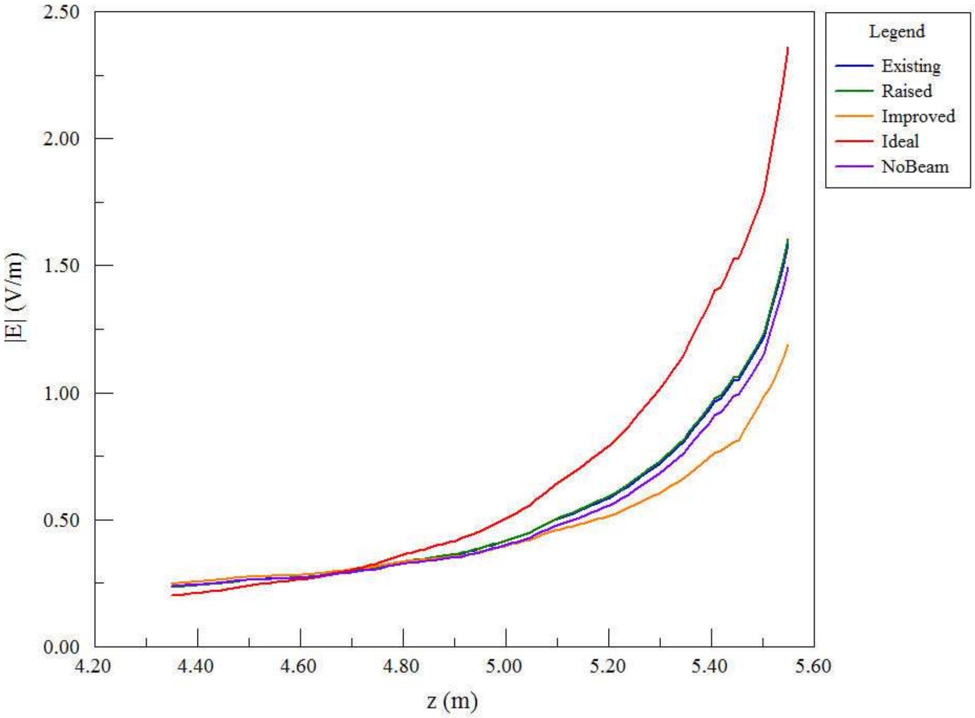

Figure 6: Variation of $|\mathbf{E}|$ along the top part of the insulator facing the switch assembly.

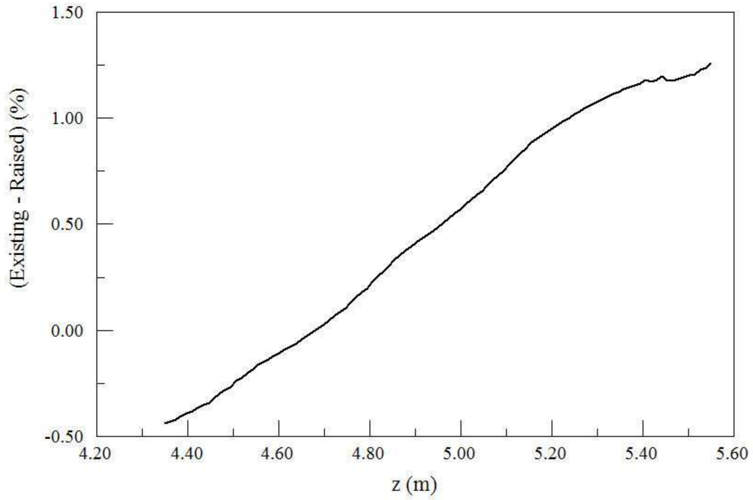

Figure 7: Difference in electric field magnitude along the scan line of Fig. 1. Relative difference between the system with the switch assembly raised 2.1 m and the existing geometry.

beam is offset by the reduced effect of a longer connecting rod. Removing the grounded beam altogether gives a small improvement (the violet curve in Fig. 6). Finally, the yellow curve in Fig. 6 shows the field variation with a larger top electrode on the breaker bushing (a sphere of diameter 1.0 m).

Although the addition of internal grading in the bushing could change details of the field distribution, my conclusion is that raising the switch assembly would not significantly change the electric field on the surface of the insulator.