# USING E-FIELD MODELING TO IMPROVE PERFORMANCE OF TRANSMISSION LINES

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## Overview

All too often when designing transmission lines, the overriding design criteria is the mechanical performance of the line. This once made complete sense - if the mechanical design does not perform, the electrical design becomes irrelevant. Today, the mechanical design of transmission lines is very robust thanks to technology innovations in structures, conductors, hardware, and insulators. It is time for line designers to take a closer look at the electrical performance of their designs to ensure that it meets the needs of the utilities. It seems that it comes to electrical performance during the design stage, the basic philosophy is "that's what we have always done." Designers should want a better understanding of how hardware, insulators, and geometry affect the electrical performance of a transmission assembly. The question then becomes "how do we know that a design is performing at acceptable levels or is optimized to deliver the best performance?" The use of Electric Field, or E-field, modeling can answer these questions. To understand this, we must ask "why use it" and "how does E-field modeling improve transmission line performance?" E-field modeling has many applications; therefore, this paper will only consider its value as it applies to high voltage transmission assemblies.

## What is E-Field modeling?

E-Field modeling is accomplished using Computer Aided Engineering (CAE) software that is capable of calculating electric field intensity of given objects and an appropriately configured computer with the necessary computational power. There are many versions of software that can be used for E-field modeling, each with their own strengths or preferred uses. Some of the software available for calculating E-fields include Coulomb, Maxwell 3D, Comsol, and Flux 3D. MacLean Power Systems (MPS) has chosen to use Integrated Engineering Software's (IES) Coulomb software package for our modeling system. The Coulomb software uses the Boundary Element Method (BEM) to solve models. BEM is a tool for the analysis of boundary value problems for partial differential equations. The term "boundary element method" denotes any method for the approximate numerical solution of boundary integral equations. The approximate solution of the boundary value problem obtained by BEM has the distinguishing feature that it is an exact solution of the differential equation in the domain and is parametrized by a finite set of parameters residing on the boundary. Use of the BEM method has several advantages. In the models used for BEM calculations, there are only 2D surface elements which are the interface regions with different materials or surfaces with boundary conditions. This greatly simplifies the modeling process. The results are more accurate due to the smoothness of the integral operator. Lastly, the analysis of unbounded structures can be solved by the BEM with minimal effort as the exterior field is calculated the same way as the interior field. This software is a powerful tool for verifying electrical performance as it pertains to corona and corona inception as well as voltage stresses on the surface of the insulator.

Assembly models are first designed using SolidWorks software. The model is based on customer's specifications and an E-field Modeling worksheet completed by the customer. The worksheet consolidates information from drawings, specifications, and acceptance criteria to one document. After the information is attained, the model can be created, making sure to keep all of the complex details to a minimum, focusing on high stress areas that increase simulation solve time.

Next, the model is imported to the Coulomb simulation software and the boundary conditions are assigned. The insulation medium is defined on the insulator volumes (glass, polymer or porcelain). Voltages are assigned to the hardware; single phase voltage ($V_{SP}$) is most often used. Hardware in contact with the conductor is assigned the $V_{SP}$ and the tower and ground are assigned 0V. Conductive components not directly in contact with either conductor or tower are assigned a floating voltage that is calculated during simulation. To confirm the assembly design, the simulated voltage is 15% higher than nominal service voltage.

After all components are assigned a voltage or a boundary condition, the software generates a mesh. The finer the mesh elements – triangles – the more detailed the output will be (see Figure 1). Then the simulation is started and the temporary file size is determined. The mesh and temporary file are both used for the internal calculations. The temporary file size is relatively large (MB–GB range). The larger the file size, the longer the simulation runtime; solution runtime can range from as little as 10 minutes to over 24 hours.

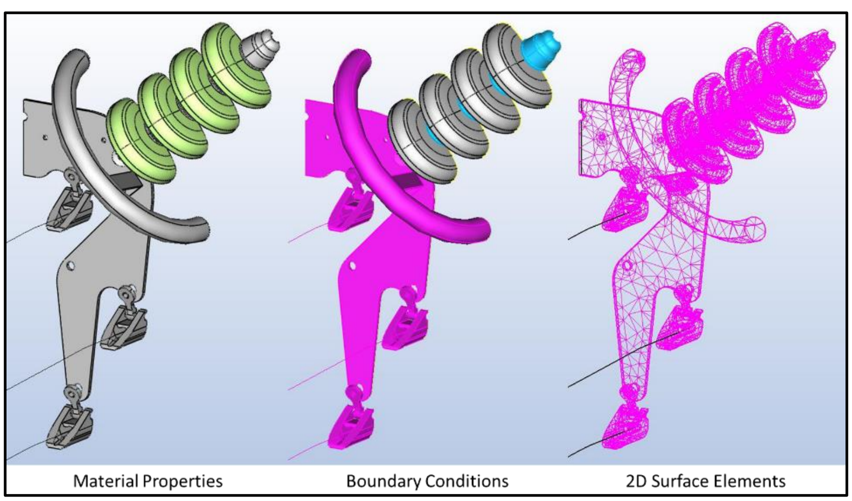


*Figure 1*

Once the simulation is complete, an E-field plot is made for the entire model and stress points are identified through visual inspection. The most common plot used is the contour plot (Figure 2), but isosurfaces and equipotential plots (Figure 3) are used on more complex assemblies. For multiphase assemblies, streamlines are used to see how the electric fields move between phases. Additional E-field plots are then created in the areas where higher electrical stresses are observed. All E-field plots are examined to confirm its validity (and not a singularity of the simulation). The resulting E-field plots are reviewed and compared with the acceptable criteria provided by the customer. A summarization would be provided of the results that includes a brief description of the simulation procedure and a list of input data and assumptions.

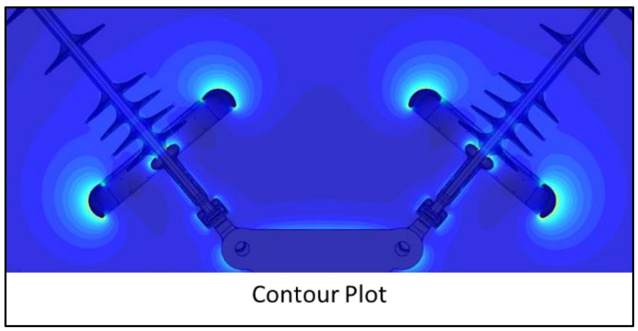


*Figure 2*

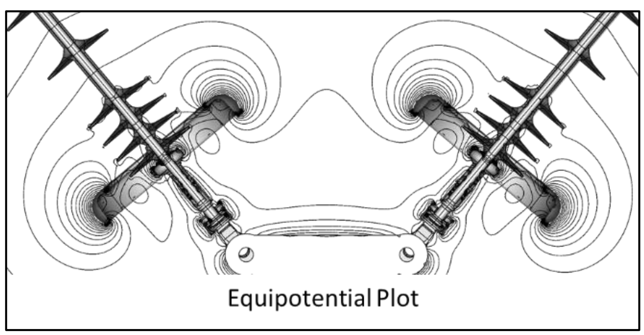


*Figure 3*

## Why E-Field modeling?

E-field modeling is a tool to determine corona inception values on transmission assemblies. Corona causes RIV and electromagnetic interference that results in line losses. Corona can also lead to premature degradation of the insulators on Non-Ceramic or polymer insulators exposed to excessive voltage stress (EPRI guideline 0.42kV/mm ->10mm). The insulator can lose hydrophobicity and be susceptible to premature aging, shortening the life expectancy of the insulators. Newer compact line designs utilizing NCI allow designers greater flexibility, but also can create more concentrated field stresses on the insulators that needs to be understood. As the use of polymer insulators has grown and transmission right of ways have compacted transmission lines, corona has become more of a concern than in the past.

Excessive electrical field stresses on ceramic strings need also be considered. Disks located on the line end of the string are more likely to require replacement. Pin corrosion, radial cracking and aging at the cement interface can shorten service life impacting the life-cycle cost of the line.

The accepted practice for determining any corona concerns meant testing in a high voltage lab. What if there was method that did not require a high voltage test lab to verify corona levels? Until recently, lab testing was the only way to determine corona inception or RIV levels. IEC 61284, NEMA Std. 107-92 and IEEE 1829 provide standardized testing parameters for RIV and corona inception of strings assemblies used in transmission assemblies. These standards do not dictate corona extinction values or minimum, acceptable RIV levels, but rather the standards are used to define testing methodology, equipment and procedures. Typically, an elevated test voltage of 110% to 135% of the rated line to ground voltage is applied. Testing requires a full-size assembly of a single phase to be constructed in the lab. HV labs of suitable size and necessary measuring equipment are limited. Likewise, there is a time element to get materials from multiple locations and to schedule lab and witnessing time. This takes time to manufacture and to secure the availability of an appropriately sized lab, both of which are often in short supply and incur expense. Depending on the size and complexity of the assembly, a single test can take up to two days; then if the design did not meet the acceptable criteria for corona inception or RIV level, the assembly has to be modified and retested.

Testing standards recognizing the limitations of testing EHV assemblies with shortened ground clearance have added procedures for use of the calibration method in testing. Here the applied test voltage and distance to the ground plane are selected so that localized electric fields of the laboratory set are energized to an equivalent voltage stress as the service condition. Usually the E-field voltage is based on the surface gradient of a sub-conductor mid-span at max operating voltage. Calibration methods are detailed in IEC 61284 and CSA C411.4-98. The test voltage is set using a calibrating bead on the AL tube used as conductor in the lab. 2D or 3D calculations may also be used to match the surface gradient on the test conductor to a predetermined service condition.

Exploring the electrical performance of alternate designs requires testing of each variation in the lab again which costs additional time, material, and expense. Lastly, does a single phase model accurately reflect the performance a three phase assembly in the field? Recent studies done by the Bonneville Power Administration in Vancouver, WA, determined that a laboratory environment did not accurately replicate field stresses of a three phase assembly using a single phase source voltage. Their work shows that adding a factor on the applied phase to ground would significantly exceed the actual field stresses by as much as

14%.[1] This could lead to false positives of corona inception causing the addition of supplementary grading protection (larger shields, sphere nuts, etc.) that can increase installation time and make future energized maintenance more difficult.

E-field modeling provides a solution to all these potential short comings in a fraction of the time and at a fraction of the expense. It also allows for a couple of additional benefits. First, E-field modeling can be used to create complete three phase models of the entire transmission structure. With this ability, models can be solved that replicate actual field conditions and avoid the inaccuracies that could result in testing at labs not matching field conditions. As previously noted, E-field streamlines for three phase models can be generated that show how each phase of the assembly impacts the E-fields of adjacent phases, a result that can't be replicated by lab testing. Second, E-field modeling software has the ability to account for actual field conditions that include temperature, pressure, humidity, and most importantly, altitude. Again, results that can't be replicated in a lab. Altitude correction formula that is commonly used below.

$$\frac{V}{V_0} = \left(\frac{\delta_0}{\delta}\right)^n$$

Where
$V$ = the voltage to be determined
$V_0$ = the specified acceptance voltage
$\delta$ = the relative air density for the altitude at which the hardware will be used
$\delta_0$ = the relative air density for the altitude of the testing laboratory
$n$ = the altitude correction exponent, commonly 2/3, but may vary from ½ to 1

With E-field modeling, the designer has the ability to evaluate assemblies without building full scale models and sending to a test lab. Design changes can simply be imported into the simulation software and solved for the desirable electrical performance criteria. Designers can evaluate their assemblies before sending it to the field for construction without ever going to a lab. When considering the tight construction timelines, design changes or improvements to existing transmission lines, E-field modeling provides the best solution.

[1] Liebhaber, Dana. "On Corona Testing of High Voltage Hardware Using Laboratory Testing and/or Simulation." IEEE General Meeting, July 17-21, 2017, Corona and Field Effects Working Group, Chicago, IL. Committee Presentation.

## How does it improve transmission line performance?

E-field modeling allows designers a tremendous amount of flexibility in developing transmission assembly designs because it allows them to model the assemblies in 3D. Aspects of the insulators and hardware assembly can be adjusted and tested to validate the intensity of the electric field and if corona will occur by utilizing these design tools to optimize corona/RIV performance. Corona discharge and RIV create line losses that reduce the efficiency of a line. Factors previously unable to be considered in the design can now be simulated. For example, designers are easily able to modify the geometry, placement, and size of grading devices. Instead of using 1.5" tubing for a grading ring, an option of 2" tubing could be incorporated into a grading shield by simply modifying the original geometry or shape. Furthermore, is a grading device required at all? Many times in history the answer was "yes"; they were generally added because "that's the way we have always done it". With E-field modeling however, a definitive result can be provided that confirms the adequacy of a design for grading protection. Proper control of the e-field stresses on insulators extends service life improving life-cycle cost of ownership. E-field modeling can also be used to adjust shed placement and size on a polymer insulator. Changes of this nature can be verified by the simulation software before an insulator is ever manufactured thus creating an enormous time saving and verifiable performance. Simulating the different component and hardware variations allows designers greater flexibility and the certainty of performance. The end product is improved transmission line performance.

## Illustration

To help illustrate the use of E-field modeling, we will explore a few examples where Efield simulations were used to optimize designs and solve existing issues that led to increased electrical performance.

A utility in the eastern US was re-conductoring and reinsulating a 345kV transmission line on existing structures with tight clearances. The decision was made to reinsulate with polymer insulators. The utility was concerned with the possible stresses that would be placed upon the sheath of the polymer insulators. The particular tower arrangement that caused the most concern was for an angle assembly with the conductor position pulled toward the structure. E-field modeling was used to simulate the E-field stresses along the insulator sheath. The model showed that the original design was reaching the shielding capacity of the assembly and that an abnormal accumulation or deficiency of flow generated an E-field intensity of 0.46 kV/mm for more than 16mm along the sheath of the insulator. Studies done by the Electric Power Research Institute (EPRI) indicate that values over 0.42 kV/mm over a 10mm span along the sheath of the insulator can affect the longevity of the insulators over time. There were two options that could be used to resolve the high E-field stresses; 1) increase the diameter of the corona ring, which would also increase the cost, or 2) displace the sheds so that the E-field more equally distributes around the line end of the insulator. The second option was chosen because it would not increase the cost and would provide similar results to increasing the corona ring diameter. To properly determine the shed placement along the insulator, the location of the high electric field was determined. The equipotential lines were evaluated on the original simulation and compared to the line plot along the sheath. It was found that the location of the first non-stacked shed, slightly above the top of the corona ring, caused an influx of electric field stress on the shed; however, shifting that shed along the sheath in the direction of the tower end of the insulator allowed for the natural dissipation of the electric field. Once this location was ascertained, shed spacing could be defined and applied to the insulator model. From the results of the new insulator simulation, it was determined that the E-field intensity along the insulator sheath was reduced to meet the customers' acceptance criteria and EPRI's recommended value of 0.42 kV/mm over a 10mm length.

A western US utility had a 230kV transmission line originally constructed in the late 1970's that covered a distance of over 1,000 miles. The line was constructed of guyed V transmission towers with insulator assemblies arranged in an I-V-I configuration. The V-string was located within the framing of the tower as shown in Figure 4. The insulators used were porcelain bells that supported a two conductor bundle of 795 Drake in a vertical orientation. The line ranged in elevation from a few hundred feet above sea level to over 5,000 ft. as it traversed through mountain ranges in the western US. In the mid 2000's, the utility increased the line voltage to 345 kV for additional capacity.

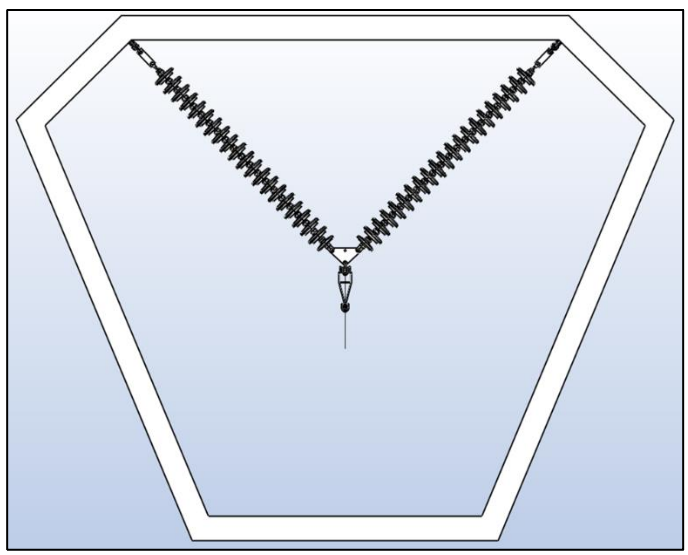

*Figure 4*

At this time, the line began to experience RIV, radio interference voltage, and nuisance line trips. The presence of excessive audible noise was an indicator that corona was present and additional line losses were occurring. The nuisance trips could be caused by a variety of reasons including contamination on the insulators. The questions then became: 1) is corona occurring; 2) what is the solution to mitigate corona on the line; and 3) can the solution address the cause of the nuisance trips? The utility hired consultants who provided partial answers, but no solutions. Their conclusion was corona was occurring and the cause of the nuisance trips was contamination of the insulators. The simple answer to the contamination issue was to increase the leakage distance of the insulators. However, could this be done on the existing structures while maintaining the necessary dry arc distances for the operating voltage? To find solutions to this question and to solve the corona issue, E-field modeling would need to be employed. MacLean Power Systems used IES' Coulomb software to develop a solution. To begin, the current condition of the assemblies had to be simulated. The configuration of the tower was modeled using drawings, pictures, and specifications provided by the customer. Maximum elevations and tightest clearances were used to simulate worst case conditions. The results from this simulation were the baseline on which to improve. The first step to providing a solution was to increase the leakage distance of the assemblies. The only way to do this within the existing structures and using the existing hardware was a proposed change to toughened glass insulators with a fog type profile as the insulating medium. This would increase the leakage distance of the insulator strings while maintaining the dry arc distances. The model for each type of insulating assembly, I-string and V-string, simulated in Coulomb (Figures 5 and 6) showed the E-field stresses along each insulator assembly. From this, MPS engineers were able to determine the areas of high electrical stresses where corona was occurring. Interestingly the model showed highest stresses on the outside I-string assemblies, rather than on the center phase V-string with the extremely tight tower clearances. Noting these areas, grading devices with specific geometrical shapes were applied to the insulating assembly models at specific points to provide targeted E-field grading (Figures 7 and 8). By designing the devices to be application specific, and not using what was readily available, there is no uncertainty of the design performance. With E-field modeling, there is a known value and an engineering solution can be derived. Using the models that were simulated in Coulomb, MPS was able to provide a solution to the problem and provided a better electrical performing assembly.

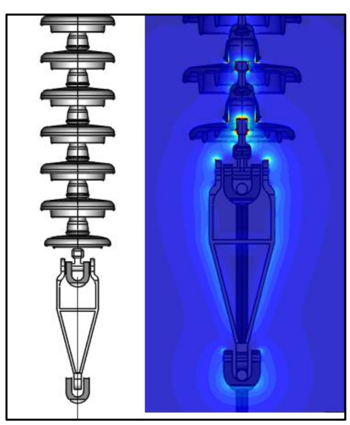

*Figure 5*

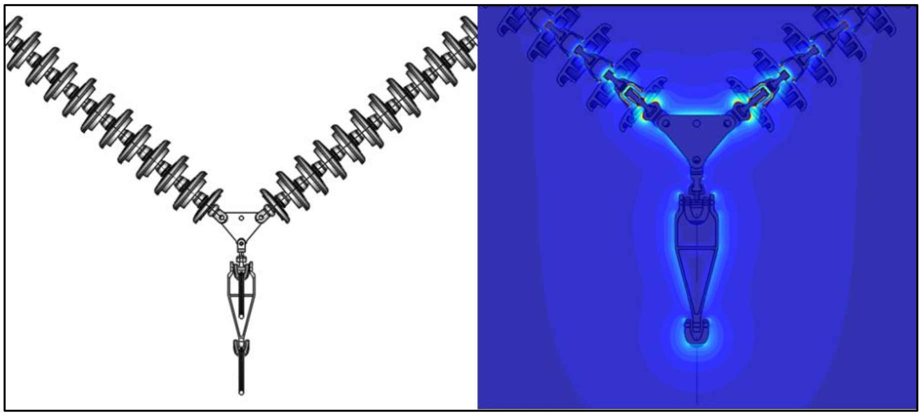

*Figure 6*

Before shielding was added to the assemblies

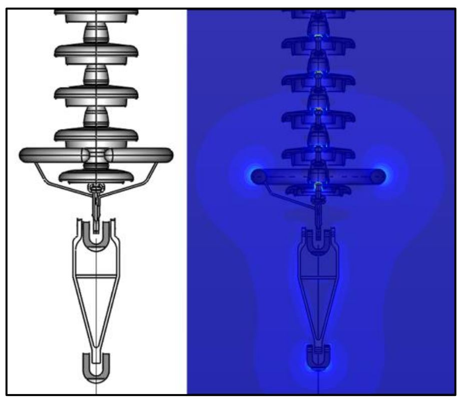

*Figure 7*

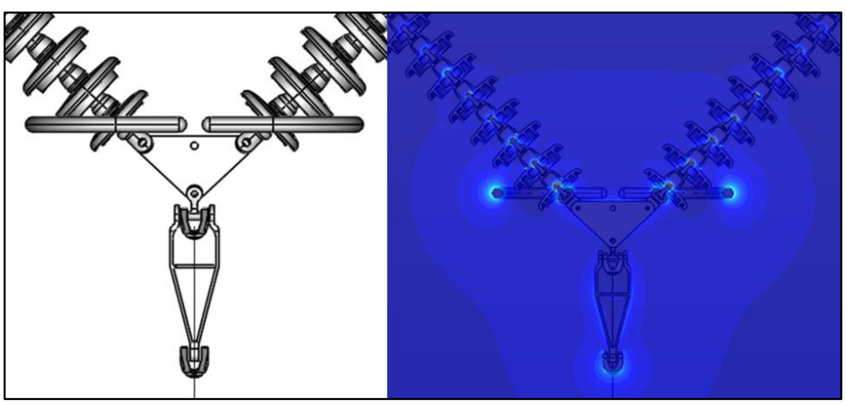

*Figure 8*

After shielding was added to the assemblies

## Summary

With the new innovations in E-field software and 3D drawing technology, more attention to standard assemblies should be examined for corona/RIV issues. E-field modeling should be used to reveal potential issues with corona/RIV on the full three phase assembly, versus just a single phase. With accurate 3-phase E-field modeling, real world simulations are more feasible than ever. A direct advantage to E-field modeling is using this tool to optimize the current assembly designs as shown in the included illustrations. An example of a more specific benefit to E-field modeling is making the insulator and hardware assembly more workable/accessible for hot-line work and maintenance. E-field modeling has gained acceptance for evaluating high voltage transmission line designs due to the equivalence of the calculations generated versus the HV lab results.