21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2016 Grid of the Future Symposium

Innovative Ground Grid Design Methodology for EHV Stations with Auto-Transformers

X. WU, V. SIMHA, R. WELLMAN
American Electric Power
USA

SUMMARY

This paper describes hands-on solid modelling experience of the safe optimal ground grid design (e.g., less copper) for a large Extra High Voltage (EHV) substation. The optimized ground grid meets the IEEE-80 standards for safety without compromising on step or touch potential thresholds. The ground grid has been designed in CDEGS using fault current flow concepts, multiple injection points simulate the actual conditions and fault currents at the substation. The method focuses on substation specific data to perform substation grounding studies and does not assume the fault current split factors, or utilize the IEEE-80 curves. The method is conceptually correct, meets safety requirements, and leads to significant copper savings. Thus, a safe and optimized ground grid for an EHV station is achievable.

KEYWORDS

Circulating Current, Local Source, Multiple Injection, Optimization, Remote Source, Split Factor

xwu@aep.com

ABBREVIATIONS AND ACRONYMS

AEP – American Electric Power, IEEE-80 – IEEE Std. 80-2013 [1], EHV – Extra High Voltage, ASPEN – Advanced Systems for Power Engineering, CDEGS – Current Distribution Electromagnetic Fields, Grounding and Soil Structure Analysis, ($3I_0$) – Total ground fault current, (I_g) – Current flowing into the grid, (I_n) – Current flowing into the shield wires from the ground grid, (I_{cir}) – Circulating current returning to the neutral of the local transformer from the fault location, 1LG – Single line-to-ground fault condition, SES – Safe Engineering Services & Technologies, MI – Multiple Injection Current Method, SI – Single Injection Current Method.

INTRODUCTION

This paper describes a practical method of modelling a large EHV station (Station S) ground grid using CDEGS software. Technical challenges and common assumptions that lead to excessive copper use and optimization techniques are discussed. The fault current data obtained in ASPEN is used to identify the contributions made by the remote sources (transmission lines connecting Station S) and local sources (auto-transformers inside Station S). The soil model in which the ground grid is installed is determined by soil resistivity tests utilizing the four-point Wenner method. The ground grid model is developed in CDEGS, and the locations of local and remote contributions are identified. A single point injection of one Amp in the grid is required to determine the ground grid resistance. The grid impedance is used in the FCDIST module to determine the fault current division via the shield wire and the ground grid. The circulating current is determined from ASPEN. The total fault current ($3I_0$) is injected into the grid at the fault location. The shield wire current components and the circulating current component are ejected out of the grid. This allows the grid current to flow into the ground grid and sets a stage to calculate the surface touch and step potentials. The touch and step potential values are compared to the threshold limits calculated as per IEEE-80 [1] in the CDEGS software. When the actual touch and step potential values are less than the threshold limits, then the IEEE-80 requirements are satisfied and no additional ground grid conductors are required.

FAULT ANALYSIS

In the past thirty years, a few publications [2]-[5] have focused on station fault current distribution and split calculations. Fault analysis is significant as the foundation of station grounding studies.

A. Fault Categories

There are two fault categories that can cause unbalanced fault currents flowing to the ground: single line-to-ground fault, and double line-to-ground fault. Based upon dividing the three-phase system into the symmetrical components (zero-, positive-, negative-sequence networks), the fault analysis problem for grounding is simplified with only considering the zero-sequence current (I_0). Because the value of I_0 is proportional to the unbalancing extent of a fault, the single line-to-ground fault is the worst-case scenario in most case studies.

B. Fault Locations

The fault locations are always chosen on the high-side or low-side buses. This is because the incoming lines/feeders and transformer banks are connected to these buses. In other words, the fault current is higher when the fault occurs on a bus. However, it is hard to determine which bus would be the worse-case scenario [5]. In AEP, the fault locations based on all buses are analyzed except for buses with voltage classes lower than 69 kV. For example, in an AEP EHV station there may be five different voltage buses – 765, 500, 345, 138 and 69 kV. In addition, the 34.5 kV and 12 kV buses are excluded from the fault analysis when they are delta-connected and without a grounding transformer.

C. Fault Components

The basis of grounding fault analysis is the total ground fault currents ($3I_0$) should return to their sources through either earth or any metallic objects. As mentioned earlier, the transformer connection plays a significant role in the fault current distribution. For example, if the fault occurs on the low-side of Δ-Y transformer in a small distribution station, this means the entire fault current will flow back to the transformer neutral through the ground conductors. In other words, only transformer neutral circulating current (I_{cir}) exists in this case.

In large AEP transmission stations, auto-transformer banks are often used. As a result, there are three components for $3I_{0:}$ ground grid current returning to remote sources via earth (I_g), neutral/shield wire current returning to remote sources (I_n), and transformer neutral circulating current (I_{cir}). This is shown graphically in Fig. 1.

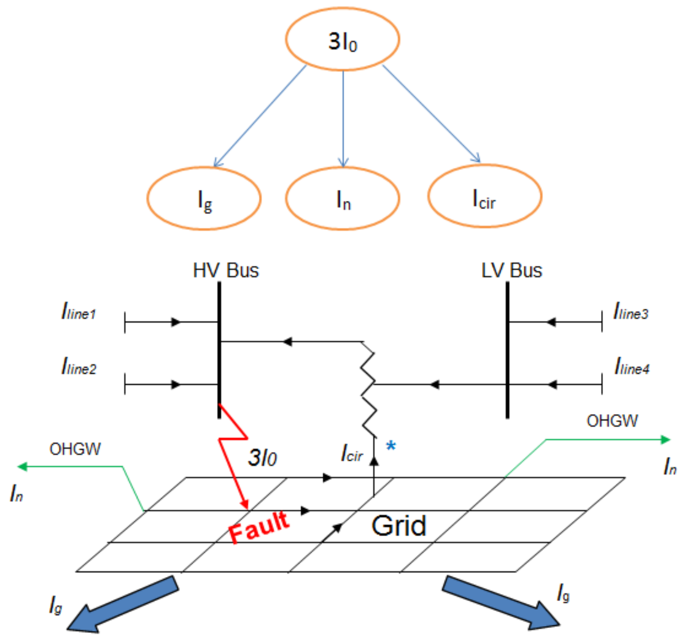
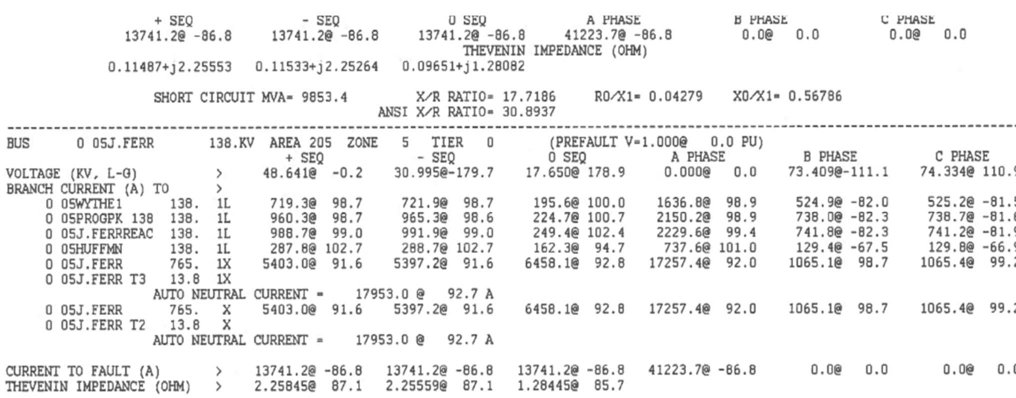


Figure 1. MI method fault current distribution

D. Fault Analysis Tools and Applications

In AEP, ASPEN OneLiner is widely used by protection & control engineers and station engineers for fault analysis. For a grounding study, faults on specific buses are simulated. As an example, the Fig. 2 shows an example ASPEN output window. Information such as $3I_0$, I_{cir}, and X/R ratio can be acquired from ASPEN.



```
              + SEQ              - SEQ              0 SEQ              A PHASE              B PHASE              C PHASE
          13741.2@ -86.8     13741.2@ -86.8     13741.2@ -86.8     41223.7@ -86.8         0.0@    0.0          0.0@    0.0
                                                          THEVENIN IMPEDANCE (OHM)
        0.11487+j2.25553   0.11533+j2.25264   0.09651+j1.28082

           SHORT CIRCUIT MVA= 9853.4           X/R RATIO= 17.7186      R0/X1= 0.04279     X0/X1= 0.56786
                                          ANSI X/R RATIO= 30.8937
--------------------------------------------------------------------------------------------------------------------------
BUS       0 05J.FERR        138.KV  AREA 205  ZONE   5   TIER   0       (PREFAULT V=1.000@   0.0 PU)
                                        + SEQ            - SEQ             0 SEQ            A PHASE          B PHASE          C PHASE
VOLTAGE (KV, L-G)            >      48.641@  -0.2    30.995@-179.7    17.650@ 178.9     0.000@    0.0    73.409@-111.1    74.334@ 110.9
BRANCH CURRENT (A) TO        >
     0 05WYTHE1        138.  1L      719.3@  98.7      721.9@  98.7     195.6@ 100.0    1636.8@  98.9     524.9@ -82.0     525.2@ -81.5
     0 05PROGPK 138    138.  1L      960.3@  98.7      965.3@  98.6     224.7@ 100.7    2150.2@  98.9     738.0@ -82.3     738.7@ -81.6
     0 05J.FERRREAC    138.  1L      988.7@  99.0      991.9@  99.0     249.4@ 102.4    2229.6@  99.4     741.8@ -82.3     741.2@ -81.9
     0 05HUFFMN        138.  1L      287.8@ 102.7      288.7@ 102.7     162.3@  94.7     737.6@ 101.0     129.4@ -67.5     129.8@ -66.9
     0 05J.FERR        765.  1X     5403.0@  91.6     5397.2@  91.6    6458.1@  92.8   17257.4@  92.0    1065.1@  98.7    1065.4@  99.2
     0 05J.FERR T3     13.8  1X
              AUTO NEUTRAL CURRENT =    17953.0 @    92.7 A
     0 05J.FERR        765.   X     5403.0@  91.6     5397.2@  91.6    6458.1@  92.8   17257.4@  92.0    1065.1@  98.7    1065.4@  99.2
     0 05J.FERR T2     13.8   X
              AUTO NEUTRAL CURRENT =    17953.0 @    92.7 A

CURRENT TO FAULT (A)         >    13741.2@ -86.8   13741.2@ -86.8   13741.2@ -86.8   41223.7@ -86.8        0.0@    0.0        0.0@    0.0
THEVENIN IMPEDANCE (OHM)     >    2.25845@  87.1   2.25559@  87.1   1.28445@  85.7
--------------------------------------------------------------------------------------------------------------------------
```

Figure 2. Example of an ASPEN result report

However, I_n are calculated utilizing the FCDIST module developed by SES. An example input window of FCDIST is shown in Fig. 3.

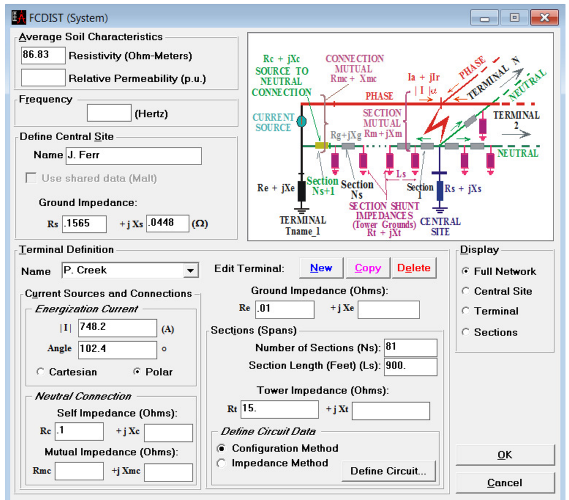


Figure 3. Example of a FCDIST input window

With the correct input data and simulation following the FCDIST manual [6], the output file will show the I_n from the central station to each specific terminal station as shown in Fig. 4.

TERMINAL NUMBER	NAME	CURRENT (A): PHASE CONDUCTOR Magnitude	PHASE CONDUCTOR Angle (deg.)	NEUTRAL CONDUCTOR Magnitude	NEUTRAL CONDUCTOR Angle (deg.)	GROUNDING SYSTEM Magnitude	GROUNDING SYSTEM Angle (deg.)
1	Dumont-Marys	3431.0	98.000	1413.3	121.93	2214.6	82.999
2	Allen	2323.0	93.000	1348.2	90.020	979.13	97.105
3	Meredian-Dum	3942.5	97.000	2527.5	93.697	1426.7	102.86
4	Robison Park	3910.0	117.00	1550.0	131.02	2435.3	108.13
5	Industrial P	1451.0	90.000	1316.5	85.333	175.34	127.65
6	Columbia	1054.0	97.000	880.62	102.39	195.66	71.968
7	Desoto-Keyst	2665.1	98.200	1430.3	93.951	1243.3	103.09
8	GM-McKinley-	1967.9	98.300	1411.4	91.266	592.87	115.25
9	Delaware-Hum	1807.8	100.40	1401.7	91.173	480.09	128.31
	TOTAL	22331.	100.25	12835.	99.727	9496.9	100.96

Figure 4. Example of a FCDIST output file

E. AEP Proposed Grounding Study Flowchart and Process

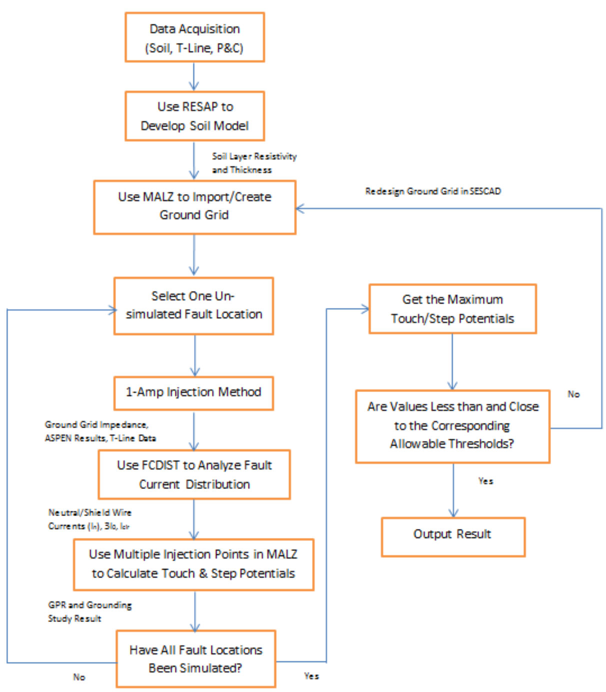


Figure 5. Flowchart of AEP Grounding Study

1. Enter and simulate soil resistance measurements using RESAP.
2. Create or import a ground grid in MALZ and use 1-Amp injection point at the selected fault location to calculate the ground grid impedance.
3. Input the ground grid impedance, remote contribution line currents from ASPEN, T-Line information (number and average length of spans, tower footing resistance, circuit configurations, and shield wire size/materials) into FCDIST, and then run simulation to get the values of I_n.
4. Use $3I_0$, I_n and I_{cir} as the injection currents at the specific locations in the MALZ module, which means there will be multiple injection points. Typically, $3I_0$ should be injected into the ground grid, while I_n and I_{cir} are ejected from the grid to the neutral/shield wires and the transformer banks, respectively.
5. Place a surface profile above the ground grid, and calculate the surface touch and step potentials of each profile point.
6. Calculate the threshold limits for the allowable touch and step potentials using X/R ratio, clearing time and surface material parameters, and compare the calculated values with the allowable values.
   a) If the calculated touch potential is lower than 80% (selected for a safety margin) of the threshold value, it is suggested to delete some ground conductors.
   b) If the calculated touch potential is equal or larger than 80% of the threshold value, it is necessary to add some ground conductors near the high-potential areas to mitigate.

CASE STUDY

Station S is a 765/345/138 kV EHV station. It combines the 138 kV (on the top left), 345 kV (on the middle left), and 765 kV (on the right) yards into one entire station yard as shown in Fig. 6. The 345 kV yard has an existing ground grid, while the new 138 and 765 kV expansion areas are still to be designed. Based on the generic rule, the expansion yard ground grid is initially designed using 30-by-30 ft meshes (as easily realized in Fig. 6). Ground conductors (4/0 stranded copper) with a total length of 119,700 ft (including the existing ground grid) are intended to be buried.

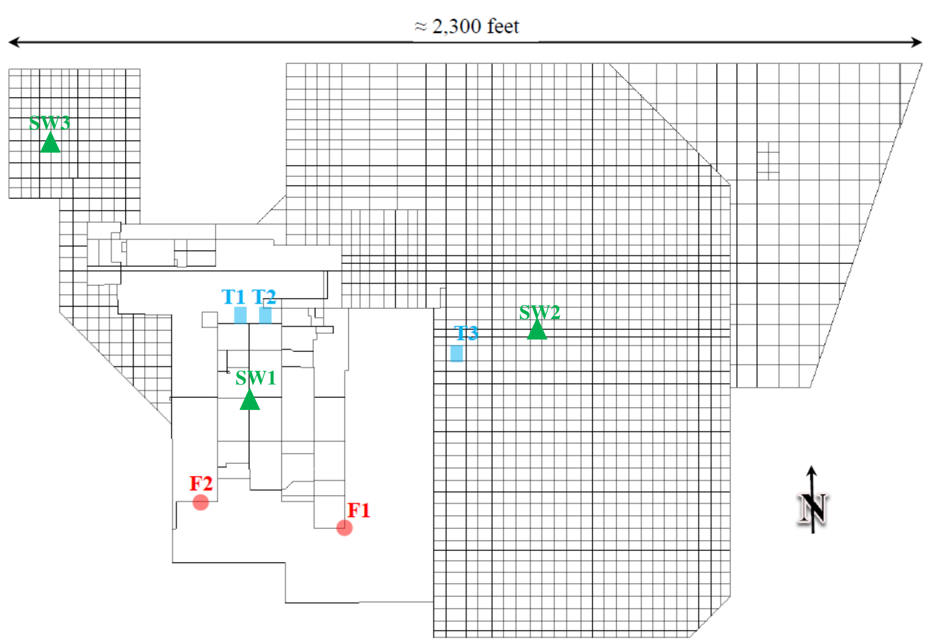


Figure 6. Ground Grid Layout

As marked in Fig. 6, “F1” and “F2” mark two selected fault locations, which are two points of the 345 kV bus. Note that the 138 kV and 765 kV bus fault locations were analyzed as well but not shown in this paper due to their smaller touch potential results. “T1”, “T2”, and “T3” represent two 345/138 kV and one 765/345 kV transformer bank locations, respectively. “SW1”, “SW2”, and “SW3” show approximate 345 kV, 765 kV and 138 kV yard locations where shield wires connect to the ground grid, respectively.

Before continuing into the grounding study process, it is necessary to determine the zero-sequence fault current based on the ASPEN result. For a 1LG fault occurring at the 345 kV bus, the ASPEN result is translated to a fault current contribution diagram as presented in Fig. 7.

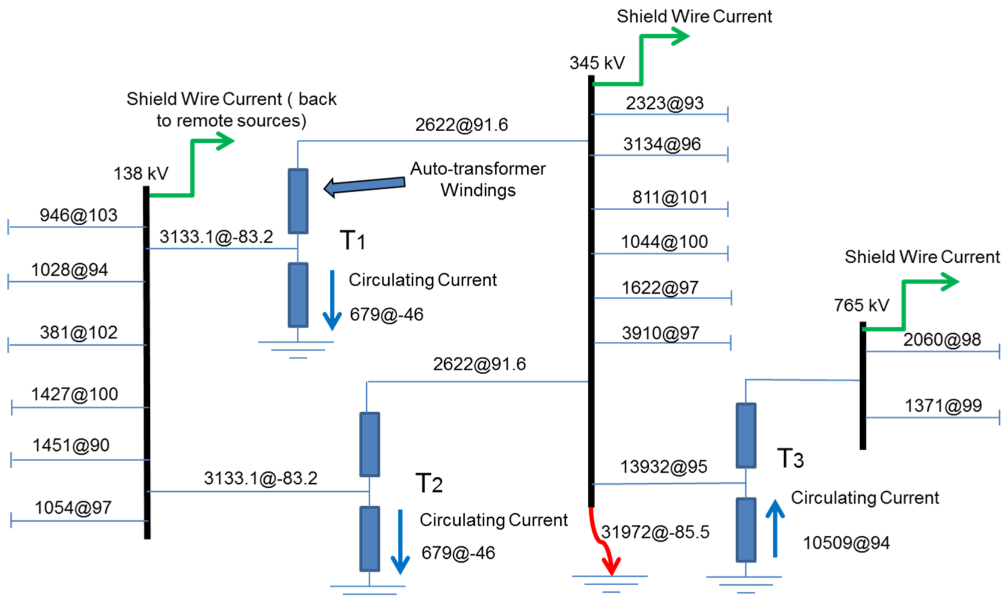


Figure 7. Diagram showing worst-case fault current flow

Note that the vectors in Fig. 7 indicate the zero-sequence fault current ($3I_0$) and include the remote fault current contributions, fault currents flowing between bus and transformer, and transformer neutral circulating currents (local fault current contributions).

The shield wire currents (I_n) noted with green arrows, must be calculated from FCDIST with input of all zero-sequence remote fault contributions from terminal stations. The results are shown in the red box of Fig. 4. On summing the vectors with the same voltage class, 345, 765 and 138 kV shield wire currents are obtained and entered into the “Energization” table displayed in Fig. 8.

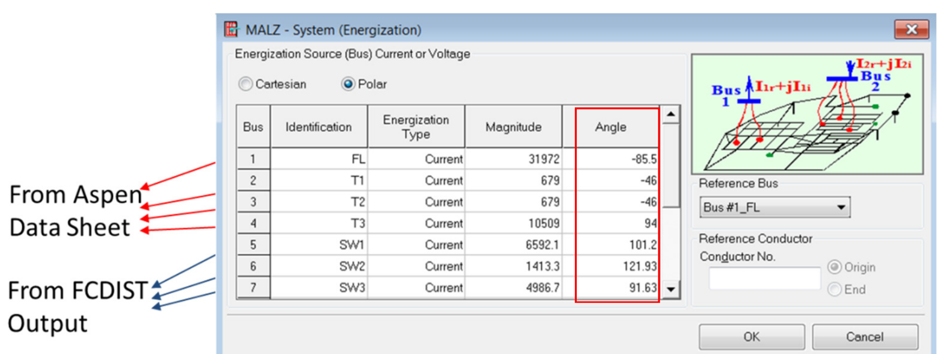


Figure 8. “Energization” input window and explanation

The touch potentials for “F1” and “F2” fault locations are calculated via MALZ with results shown in Fig. 9 and Fig. 10, respectively. Note that the step potential calculations and results are not presented in this paper since step potential is typically not the decisive ground grid design parameter comparing to the touch potential. Based on the analysis, the worst-case scenario is with the fault at the 345 kV bus “F2” location as shown in Fig. 10, which produces the highest touch potential.

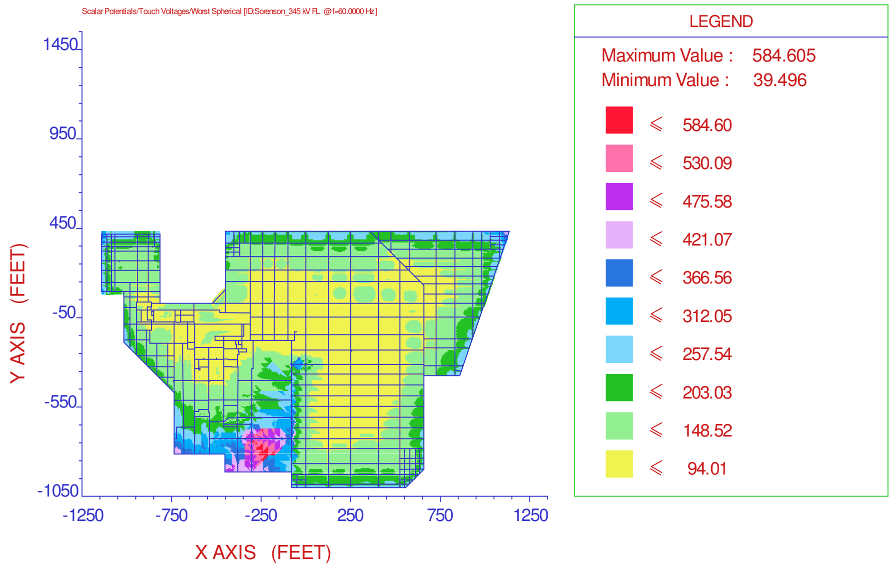


Figure 9. Touch potential magnitude plot for “F1” fault location

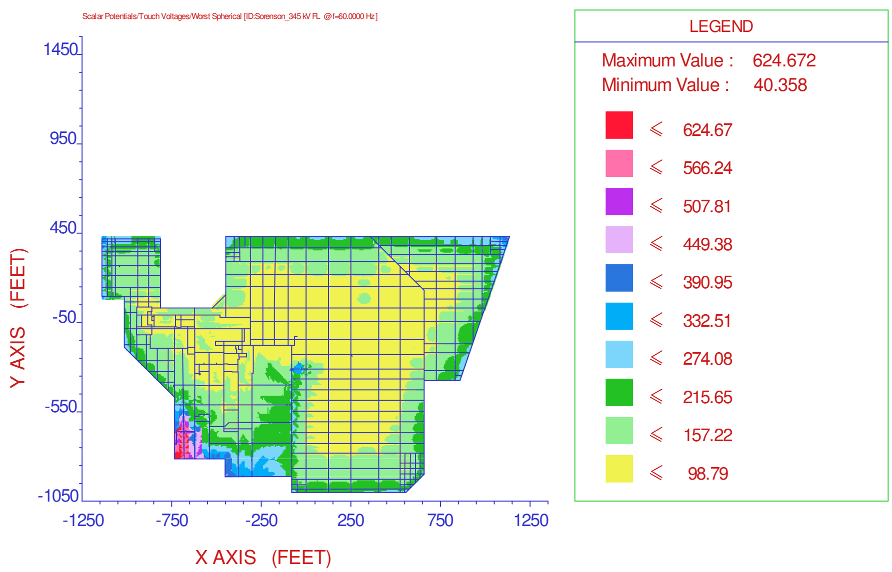


Figure 10. Touch potential magnitude plot for “F2” fault location

For the final step, the threshold limits for the allowable touch potential are calculated: 822 V, using 20 cycles (0.33 s) as the fault clearing time, 3000 Ω-m as the surface material resistivity, 4 inches as the surface material depth, and 10.53 as the X/R ratio obtained from ASPEN. The calculated worst touch potential value (as shown in Fig. 10) is 625 V, which is 76% of the maximum allowable value (822 V). Therefore, the ground grid (in Fig. 9 and Fig. 10), with total ground conductor length of 64,230 ft, is a safe and optimal design.

For comparison, the initially designed ground grid (the first-round design by using 30 by 30 ft meshes in the expansion areas) is analyzed using MI method and its touch potential plot is shown in Fig. 11.

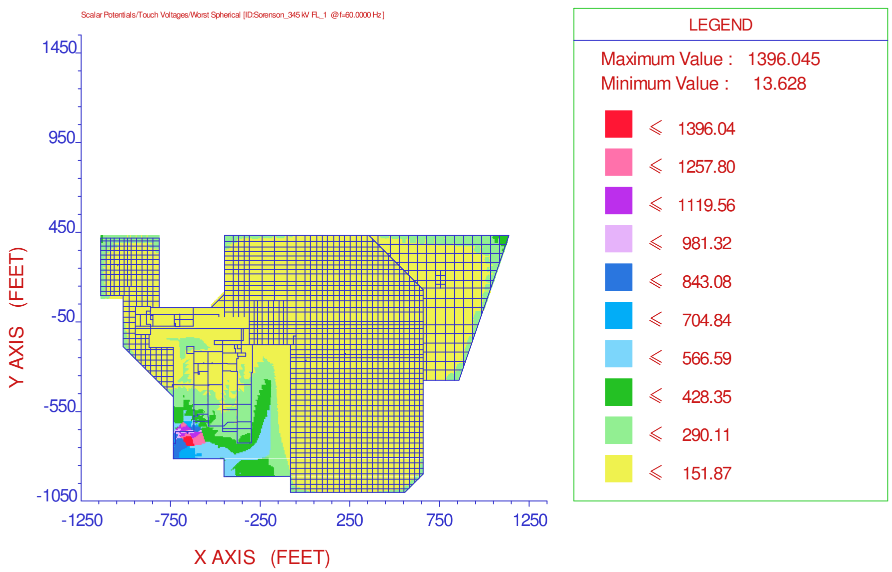


Figure 11. Touch potential magnitude plot for initial ground grid

Even though the intial grid buried 55,470 ft more ground conductor (119,700 - 64,230), the worst calculated touch potential is 1,396 V, much higher than the optimized design (Fig. 10). This is because an excessive amout of ground conductors are wasted in the middle of the expansion areas instead of the "red" areas (as shown in Fig. 11). Also, more ground conductors lead to larger fault current flowing through the grid.

As a result, we suggest to start the initial grid design from the minimum structure/equipment needed ground grid (which just covers the structure/equipment areas in order to conviniently bond the structure/equipment grounds to the nearby ground grid sections for saving pigtails and labors) and follow the optimal design flowchart and process mentioned in previous section.

In addition, another comparison between MI and SI method is described below. The application of SI method follows the steps below:

- Distribute EHV transformer circulating current into remote fault current contributions (terminal source currents).
- Model the total fault current using FCDIST to obtain I_{g1} and I_{n1}, which are different from the true values of I_g and I_n.
- Use I_{g1} as the injection current at the fault location in MALZ module, which means there is only one injection point.

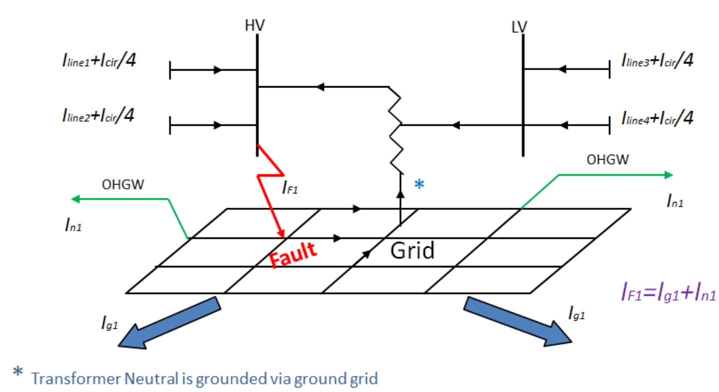


Figure 12. SI method fault current distribution

By utilizing the SI method, the “optimized” ground grid is designed as shown in Fig. 13. The corresponding calculated worst touch potential is 636 V, which is 77% of the maximum allowable value (822 V). However, the corresponding total ground conductor length is 69,820 ft, which requires 5,590 ft (69,820 - 64,230) of extra ground conductors. Considering the unit cost of material and labor as $15/ft, the cost saving is $83,850 ($15/ft * 5,590 ft) compared to the SI method. More importantly, the MI method is more accurate and closer to the real site conditions, especially when designing EHV station (with auto-transformers) ground grids. The SI method is recommended for distribution stations by modeling the 1LG fault on the high-side of Δ-Y transformer based on two reasons: firstly there is no auto-transformer neutral circulating current (I_{cir}), which means the I_{g1} and I_{n1} equal to I_g and I_n, respectively; secondly the distribution station is so small that the shield wire ejection point(s) could be assumed at the same location as the fault current injection point, meaning I_g (calculated as $3I_0$-I_n) is the single injection current.

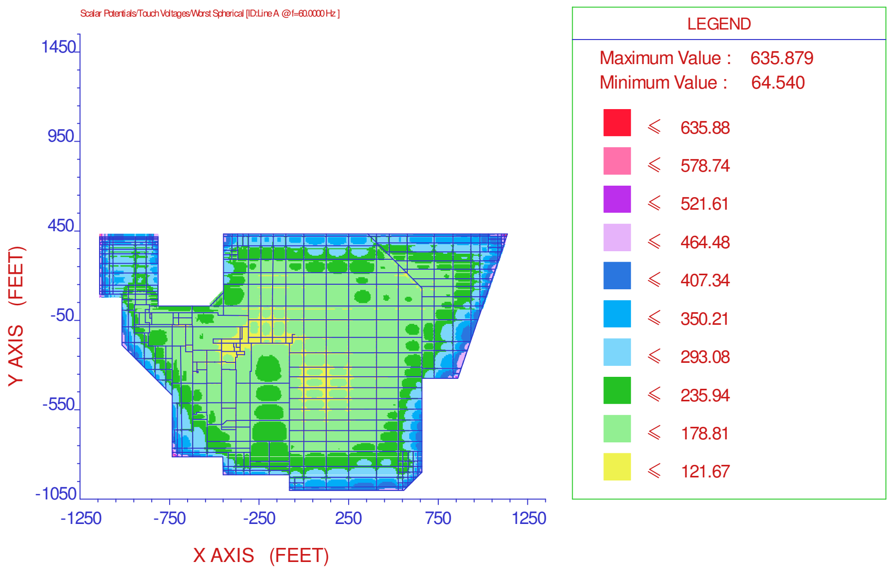


Figure 13. Touch potential magnitude plot using SI method

CONCLUSIONS & FUTURE WORK

This paper describes the design of a safe optimal ground grid for a large EHV station with auto-transformers (Station S). Conservative approaches, such as not calculating the station specific fault current split factor or single injection of grid current (SI method), can lead to the excessive use of copper. By utilizing the optimization process described in this paper, a safe ground grid design has been achieved with using less copper.

BIBLIOGRAPHY

[1] IEEE Guide for Safety in AC Substation Grounding, IEEE Std. 80-2013.

[2] F. P. Dawalibi, “Ground fault current distribution between soil and neutral conductors,” IEEE Trans. Power App. Syst., vol. 99, no. 2, pp. 452-461, Mar./Apr. 1980.

[3] D. Garrett, J. Mayers, and S. Patel, “Determination of maximum substation grounding system fault current using graphical analysis,” IEEE Trans. Power Del., vol. 2, no. 3, pp. 725-732, Jul. 1987.

[4] Ma, J., Zhao, X., F. P. Dawalibi, “Practical considerations for fault current split computation in power system,” in The International Conference on Electrical Engineering, 2009.

[5] J. Ma and F. P. Dawalibi, "Modern computational methods for the design and analysis of power system grounding," in Proceedings of the 1998 International Conference on Power System Technology, vol. 1, Aug. 1998, pp. 122-126.

[6] CDEGS Software Package, Safe Engineering Services & technologies ltd., Montreal, Quebec, Canada, November 2002.