SIMPLIFIED TWO LAYER MODEL SUBSTATION GROUND GRID DESIGN METHODOLOGY

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ABSTRACT

This paper presents a simplified approach to the design of substation ground grids in non-uniform soil conditions. The procedure is based on the interpretation of principles enunciated in the IEEE Standard 80-1986 [1], with the supporting data having been obtained from actual field tests [2] on substation ground grids.

INTRODUCTION

The equations presented in the IEEE Standard 80-1986 are based on homogeneous soil conditions; while in actuality most soils exhibit variable resistivity with depth of measurement. In our service area the typical value of resistivity for the top soil ranges between 1000 to 2000 ohm-meters, (values of 4000 ohm-meters and higher have been measured). The average resistivity down to approximately 50 feet is typically 500 ohm-meters or less. Prior to our field tests the analysis of our grid designs were difficult. This was due to uncertainties brought about by the proper selection of resistivity values to be used in the equations involved. A previous paper presented the results of tests performed to develop practical design guidelines for the conditions in our service area [2].

This paper reports the present philosophies in effect at Florida Power Corporation regarding the application of the IEEE Standard 80-1986 equations.

An example of the concepts at work is shown in Appendix I.

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BASIC CONCEPTS

One of the most important findings of the test program, in addition to determination of proper input values to use in the equations, is the need to study the grounding system under design with all the elements included. Therefore it is essential that calculations be performed which do not segregate values as if they were independent from each other.

The mesh voltage, ground potential rise (GPR), ground grid resistance, grid current, overhead ground wire (OHG) and neutral conductor influence, etc., need to be treated as an interdependent system.

The following is a description of each item as they are used in our computer model, based on the results of the field tests and subsequent analysis of field data as it relates to substation grounding theory.
The definitions of the individual terms, used in the document, are listed on page 5.

SHORT CIRCUIT CURRENT

To begin with, the maximum available phase to ground fault current is obtained from a short circuit study program. The site is analyzed to determine the worst case fault as it relates to the grounding system and this current is used to assess the safety of the initial proposed substation installation.

It is well known that most short circuit programs do not include the resistance of the grid in the calculations and care must be exercised if this resistance is to be considered. The reason for this caution is that overhead ground conductors and neutral conductors will reduce the system resistance (parallel combination of grid, neutrals, OHGs, etc.) as seen by the ground fault current to something less than one (1) ohm. This low value is typically the one to be used in the recalculation of the ground fault current. Due to the inherent low value of the system resistance at the substation site, we opted not to recalculate the fault current value.

To account for future increases of fault current levels, a second study is made utilizing the 1.5 growth factor multiplier suggested in the IEEE Standard 80-1986. The expected future additional OHGs and neutrals are included in the second study.

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For some special cases, higher values of the growth factor multiplier is used and again the maximum expected number of future external ground returns are included.

Case studies indicate that in most instances, the worst case scenario is a fault inside the substation with the fault source being remote from the substation.

For checks on line faults, the resistance to remote ground of the neutral or OHG is used as a limit. That is, the maximum fault current would be the phase to ground line voltage divided by the resistance to remote ground of the neutral or OHG.

CURRENT DIVISION

The current division is determined for each site for the initial installation as well as the expected final layout (future). This is done in order to assess the amount of fault current flowing from the substation grid wires into the earth return or vice verse.

To determine the grid current the values of grid resistance in parallel with the resistance of the overhead ground and neutrals is used in a current divider network. In cases where "deep driven" ground rods are deemed necessary, the additional current division provided by the parallel resistance of the rods is taken into consideration.

The value of the grid resistance is determined as described in the section dealing with that subject and the values of resistance to remote ground of each of the external neutrals and overhead ground wires is assigned a value of two (2) ohms.

The selection of this value was based on the results of the field tests which indicated values ranging from 1.5 to 2.4 ohms and also based on comparisons made with published data by others, [2][3][4][7].

Based on this methodology, the grid current, Ig, for the example shown in Appendix I, results in 16 percent of the total available fault current. This compares well with Fig. 2 of reference [7] which indicates a value of 17 percent for the same parameters.

RESISTIVITY OF THE ROCK LAYER

Our standard is to use a six (6) inch layer of rock material at the substations for safety reasons as well as weed control and some fire control.

Presently it is our procedure to qualify the material proposed to be furnished by the supplier by performing an electrical test on a sample of the material in order to obtain the resistivity value.

The rock material now used is ASTM # 4 size lime rock which exhibits a measured wet value of 6,000 ohm-meters and a dry value of over 300,000 ohm-meters.[2]

During the safety assessment of the substation ground grid it is important to keep in mind the relative resistivity values of the surface material from the wet value to dry value.

For example, at a given time period when the soil is dry possibly resulting in larger mesh voltages (might not be larger due to the effects of additional current division) the resistivity of the rock layer will be at a much larger value. This effect allows greater mesh voltages to be safely tolerated inside the grid area. At this time we are not using the rock "decrement factor" since our standard use of six (6) inches of rock material would result in a decrement factor close to one (1). In addition, the selection of the measured wet resistivity value of the rock material combined with the fact that the formula 3ρ is based on a copper plate in contact with the rock material provides adequate conservatism.

GRID RESISTANCE

The IEEE-80 formula for the ground grid resistance to remote ground:

$$R = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} + \frac{\rho}{L_t}$$

does not specify which value of resistivity is to be used in the formula for non-uniform soil conditions, i.e. upper layer or lower layer.

Presently we perform a soil resistivity survey at each site using Wenner's Four Point Method obtaining the average resistivity down to five (5) foot, fifty (50) foot and one hundred (100) foot spacing.

The average value of the fifty (50) foot spacing is used on the first term of the equation and the average value of the five (5) foot spacing is used in the second term. The theory behind the selection of these values to be used in the equation was based on resistance calculations made on actual grid designs that were later tested in the field to obtain the correlation.[2]

In some of the technical literature it is indicated that the predominant factor in the value of grid resistance is the first term $\rho/4\sqrt{\pi/A}$ which is controlled by the grid area.[1] During our investigation it was determined that large errors in the calculated value of resistance can be incurred if the second term ρ/L_t is ignored. This is especially true when the resistivity of the top layer is much greater than that of the deeper layers.

MESH (TOUCH) AND STEP VOLTAGES

The formula for the mesh voltage:

$$Em = \rho\, Km\, Ki\, Ig / L_t$$

could give a varied number of calculated voltage values depending on the resistivity value used in the formula.

The value used in our design is the measured average resistivity of the five (5) foot layer.

This value was again selected based on comparisons between calculated values and field test data and re-enforced by the predictions of others.[2][5]

According to reference [1], humans can tolerate much higher voltage values for step voltages conditions. This is in part due to the fact that a much larger voltage is required to produce the same current in the heart region compared to the touch voltage condition. For the calculation of the tolerable step potential we selected a conservative value of five (5) times the step voltage

$$E_S = (1000 + 6\rho_S) \times 5 \times (0.116/\sqrt{t})$$

As a general rule if the touch voltage criteria is met inside the grid area the step voltage criteria will also be met. However, this may not be the case in the area surrounding the substation external to the grid. The field tests, showed the measured step voltages values to be approximately 20 percent of the maximum mesh voltage [2].

SUBSTATION AREA (A) AND KM KI FACTORS

For grid design purposes, the substation site is converted to a perfect square by determining the total area encompassed by the grid proper and taking the square root of the area to obtain an "equivalent side length".

The perfect square and length are then used in the calculations for N, L, R, Km, Ki, etc.

One constraint placed on the product of Ki Km is to limit the value to 2.5.

This value again resulted from the data obtained during the field tests [2], and is based on our typical field conditions and design parameters.

CLEARING TIME

In our system the typical clearing time for 230 Kv and above is less than 10 cycles, while the clearing time for the lower transmission voltages is less than 20 cycles.

For the purpose of the design calculations a standard time of 30 cycles was selected for all transmission voltage classes. This was done in order to standardize the time element and to provide some safety margin to account for reclosing and possible relaying back-up times.

Presently, the decrement factor used is one (1), due to the selected clearing time of 0.5 seconds.

GROUND RODS

In this area we take a different approach than the one suggested in the IEEE Standard 80 to determine the effects of installing ground rods.

As a general rule ground rods are not installed in the ground grid system unless safety of personnel can not be met with the conductors alone. In addition, GPR considerations or economics may indicate an advantage in the use of rods at a particular site.

It is our experience that when deep driven rods are installed in soils that have resistivities which vary greatly with depth, the benefits of the rods on the grounding system is greater than predicted by the IEEE Standard-80 formulas. The approach we take, is to use the IEEE Standard-80 formulas used when ground rods are not installed in order to obtain the required design values for the site's safety assessment.

If rods are deemed necessary, the parallel resistance of a predetermined number of rods is then introduced in the calculations to obtain the site's new values of the grounding system resistance, grid current, GPR, etc.

The rods are installed outside the perimeter wire. The placement of the rods outside the grid is based on field data that show their resistance as parallel combinations with the grid resistance when installed outside and a fourth of this value when installed inside.

The resistance of the rod is calculated using the classical formula:[6]

$$R = \frac{\rho}{2\pi L_r} \ln \frac{L_r}{d_r}$$

in which the resistivity of the lower layer, in contact with the rod is utilized.

Table I shows the effects of "deep driven" ground rods from an actual test performed on a de-energized grid.

Table I

GRID VS GRID PLUS GROUND ROD VALUES COMPARISON

SET-UP NO.RODS ---	GRID RESIS. OHMS	ROD RESIS. OHMS	SYSTEM RESIS. OHMS	MESH VOLT. VOLTS M1	M19	GPR VOLT. VOLTS
0	17	--	17	9.8	15.3	38.7
1	17	14.4	8.34	4.9	9.0	22.0
2	17	11.1	5.1	3.3	4.8	14.9
3	17	12.7	3.8	2.5	3.8	11.6
4	17	9.6	2.9	2.0	2.9	9.1

M1 AND M19 ARE THE VALUES FOR MESHES 1 AND 19 RESPECTIVELY

GROUND POTENTIAL RISE AND REMOTE GROUND

The GPR can be calculated one of two ways:

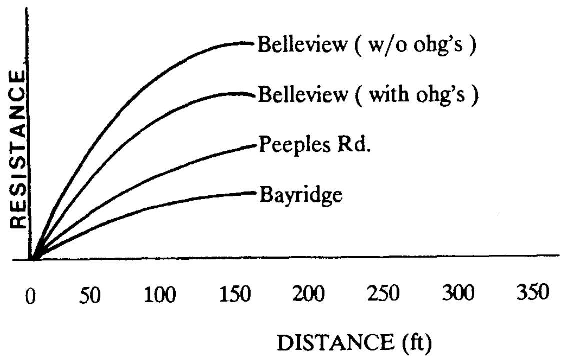
1) The total available phase to ground fault current multiplied by the "ground system resistance" (parallel combination of ground grid resistance, neutrals, OHGs, and ground rods resistance). This would be the resistance read with a ground resistance measurement instrument at an energized site.

2) The substation ground grid resistance multiplied by the current through the grid only (Ig determined by current division).

The resistance value used in case 1 (system parallel resistances) is typically less than one (1) ohm; and the resistance value in case 2 (grid only) for our normal soil conditions is typically larger than one (1) ohm.

One area that developed from our test data that is of great interest to us is the indication that the location of remote ground in non-homogeneous soil conditions appears to be much closer than predicted by the theory (Bodle curves), based on substation size.

Figure 1 shows portions of the ground resistance curves for three of the substations tested. The location on the curve just past the knee represents the distance to remote ground.



SUBSTATION GRID SIZE :

Bayridge : 228 * 236 ft
Peeples Rd : 150 * 110 ft
Belleview : 262 * 202 ft

FIGURE 1. Remote Ground Locations

For these three substations remote ground was found to be 150 to 200 feet away. This area is worth further investigation.

CONCLUSION

This paper presents a simplified approach for the design of substation ground grids in difficult soil conditions.

The method presented includes a description of the procedure used to determine the effect of the various parameters which influence the grid design.

This design practice was the culmination of a two year study during which field tests were performed on several installed grids to obtain the required corroboration of the philosophies introduced.

We are grateful for the efforts and encouragement of many individuals and departments within Florida Power Corporation. Without them this work could not have been accomplished.

REFERENCES

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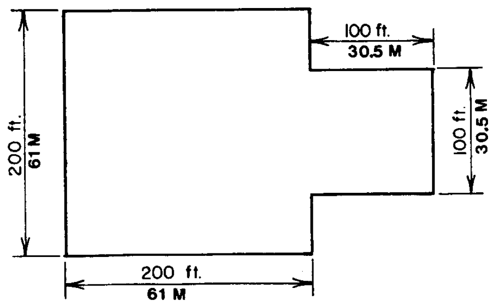
BIBLIOGRAPHY

J. Lazzara was born in Tampa, Florida, on June 13, 1940. He received his B.S. degree in Electrical Engineering from the University of Florida in 1965. That same year he joined Florida Power Corporation and has since held various positions in the Relay Design, Substation Maintenance and Testing, and the Substation Design Departments. Mr. Lazzara is presently the manager of the Relay Design Dept., is a registered Professional Engineer in the State of Florida and also is a member of the EEI Electrical System and Equipment Committee.

N. Barbeito was born in Guantanamo, Cuba on March 8, 1946. He received his B.S. degree in Electrical Engineering from Christian Brothers College in Memphis, Tenn in 1968. In 1969 he joined Florida Power Corporation as an engineer in the Substation Design Department. He has worked in the areas of Substation Design, Relay Design and the Substation Maintenance and Testing Departments. Mr. Barbeito is presently a Senior Engineer in the Transmission and Substation Engineering Services Department. Mr. Barbeito is a member of the IEEE Substation Committee and serves in several working groups.

APPENDIX "I"



DESIGN INFORMATION

GRID AREA = A = 50,000 square feet

RESISTIVITY = ρ_1 = 1,000 ohm-meters, top layer.

RESISTIVITY = ρ_2 = 300 ohm-meters, lower layer (50 ft.)

RESISTIVITY = ρ_3 = 200 ohm-meters, lower layer (100 ft.)

FAULT CURRENT = Ip-g = 10,000 initial, 15,000 future

CLEARING TIME = t = 0.5 seconds

NUMBER OF DISTRIBUTION NEUTRALS = 2 initial, 8 future

NUMBER OF TRANSM. OVERHEAD GROUNDS = 2 initial, 2 future

DIAMETER OF GRID WIRE = d = 0.0127 meters

GRID BURIAL DEPTH = h = 0.4572 meters

ROCK LAYER RESISTIVITY = ρ_s = 6,000 ohm-meter (ASTM #4 lime rock)

GROUND ROD LENGTH = Lr = 22.86 meters

GROUND ROD DIAMETER = dr = 0.0127 meters

GROUND ROD RESISTANCE = Rr ohms

NEUTRALS AND OVERHEAD TRANSMISSION GROUNDS RESISTANCE = (Constant) Rd, Rt = 2 Ohms

RESISTANCE OF THE CONNECTED GROUNDING SYSTEM = Rs

NUMBER OF GRID CONDUCTORS = N

MESH SIZE = D

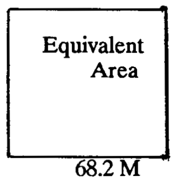
TOTAL LENGTH OF GRID CONDUCTOR = Lt

OTHER PARAMETERS AS DEFINED IN REFERENCE [1]

SAMPLE CALCULATIONS

SUBSTATION AREA = 50,000 sq.ft. x 0.093 m^2/ft^2 = 4650 sq m

EQUIVALENT SIDE = $\sqrt{A} = \sqrt{4650}$ = 68.2 meters



PARALLEL RESISTANCE OF EXTERNAL GROUNDING SYSTEM, (neutrals, overhead grounds) = Rtd = Rs

Rtd = 2 ohms / Number of attached grounds

= 2 / 4 = 0.5 ohms, Initial

= 2 / 10 = 0.2 ohms, Ultimate Layout

THE FOLLOWING CALCULATIONS ARE BASED ON A 20 ft x 20 ft MESH, (6.1 m x 6.1 m). THERE IS NO SPECIFIC REASON FOR THE SELECTION OF THE MESH SIZE FOR THIS EXAMPLE. OTHER VALUES FOR DIFFERENT SIZE MESHES ARE LISTED IN APPENDIX II FROM THE COMPUTER CALCULATIONS.

GROUND GRID RESISTANCE = Rg = $\frac{\rho}{4}\sqrt{\frac{\pi}{A}} + \frac{\rho}{L_t}$

$$= \frac{300}{4}\sqrt{\frac{\pi}{4650}} + \frac{1000}{1661}$$

$$Rg = 1.95 + 0.6 \approx 2.55\ \Omega$$

MAXIMUM ALLOWABLE TOUCH VOLTAGE, Et = $(1000 + 1.5\rho_s)\ 0.116/\sqrt{t}$

$$= (1000 + 1.5 \times 6000)\ 0.116/\sqrt{0.5}$$

Et = 1641 volts

GROUND ROD RESISTANCE = Rr = $\frac{\rho}{2\pi L_r} \text{Ln} \frac{4 L_r}{d_r} \approx \frac{200}{2\pi\, 22.9} \text{Ln} \frac{91.6}{0.013} \approx 12.33\ \Omega$

NUMBER OF HORIZONTAL WIRES = N = (Equivalent side / D) + 1

1

= (68.2 / 6.1) + 1

N = 12.2

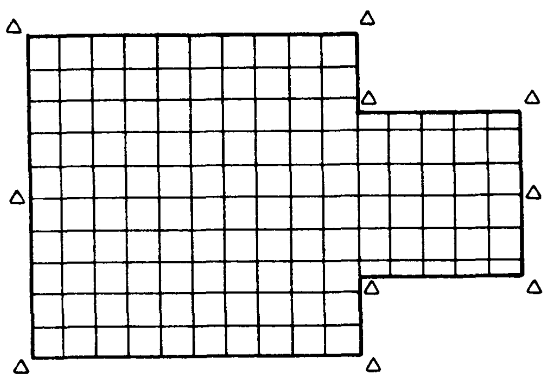
CORRECTION FACTOR = Ki = 0.656 + 0.172 x N

= 0.656 + 0.172 x 12.2 = 2.75

APPENDIX II

COMPUTER CALCULATED VALUES

MESH SIZE FT (D)	MESH SIZE M (D)	PARALLEL CONDUCTORS QTY. 1 SIDE (N)	WIRE LENGTH M (Lt)	MESH VOLTAGES INITIAL NO RODS	INITIAL RODS 10	FUTURE NO RODS
50*50	15.25	5.5	746	3333	2466	2172
40*40	12.20	6.6	899	3053	2264	2000
30*30	9.15	8.5	1153	2692	2003	1776
25*25	7.63	10.0	1356	2465	1837	1633
20*20	6.1	12.2	1661	2189	1635	1456
15*15	4.58	16.0	2169	1839	1377	1230
10*10	3.05	23.4	3186	1366	1026	919



Denotes ground rod location. △

Mesh size:
20'x 20'

Total wire:
1740 M ≥ 1661 M

Discussion

DR. F.P. DAWALIBI (SES, Montreal, Quebec Canada):

This paper should prove to be of great value not only to design engineers but also to researchers and software developers. The discusser is aware of the many field measurements conducted by the authors in recent years and hopes that other interested readers will make good use of the experimental results published in this paper and in Reference 2 of this paper.

The field measurements presented here provide both grounding system resistance and touch potentials at various locations on the earth surface above the grounding system. Because there is little published data on measured touch potentials involving full-scale grounding systems, the information in this paper is useful to those who wish to refine the predictive capabilities of their analytical models, particularly for two-layer earth models.

It is important however to caution the reader that the empirical method proposed by the authors to predict the performance of grounding systems is probably not valid for a majority of cases in which soil characteristics are different from those exhibited in the region of Florida involved in the study. It is the discusser's opinion that trying to match a two-layer or multi-layer soil model with measurements at only two points (namely at 5 and 50 foot spacings) will work only if a specific shape of the apparent resistivity curve is explicitly or implicitly presumed. In other words, a large number of curves will pass through a given pair of points unless some assumptions are made to restrict the shape of the curves to a certain class. The authors' opinion on this point would be appreciated.

Manuscript received February 20, 1990.

Jacques Fortin, (Hydro-Quebec): The authors have to be congratulated for publishing a paper based on field tests. Other utilities should be encouraged to perform similar tests.

As illustrated in Appendix I, the proposed simplified methodology seem to be straight foreward and mainly based on the current division.

Without rods, the current flowing outsite the substation for initial and final stage is respectively 84% and 93% of I p-g. Would the authors indicate the corresponding proportion for the selected grid design and illustrate how the ground rod resistance (22.9 m) is taken into account?

A possible top soil resistivity of 1000 $\Omega \cdot m$ is mentioned in the introduction of the paper. Have touch voltage and allowable touch voltage been considered outside the substation?

The grid current is established by solving the parallel current divider network (R_g 11 R_{td}). The assigned value of 2 Ω per conductor for R_{td} was based on field test performed in the Florida Power Corporation area. Have the authors some figures from field tests to compare this value for initial and final stage at the same substation? Usually, a distribution neutral conductor for each feeder leaving the substation is connected on a unique conductor in the distribution plant. Additional feeders will add conductors from the substation to that distribution plant neutral conductor. The ground resistance of that conductor should be independent of the number of feeders. The extrapollation up to the ultimate resistance R_{td} dividing an assigned value by the number of conductors may affect greatly the accuracy of the grid current as well as the actual mesh voltage.

Manuscript received March 1, 1990.

BALDEV THAPAR and **ARUN BALAKRISHNAN** (Montana State University, Bozeman, MT.): The authors have reported greatly needed important work of correlating the field data with the analytical solution obtained with the simplified equations for the grounding systems at the substations of the Florida Power Corp. However there is no proof that the simplifications proposed in the paper are applicable to all practical cases. In fact for some cases the procedure suggested in the paper may give very erroneous results. Some of these cases are given below:

1. The resistivity of the soil to be used in the simplified formulas given in IEEE Standard 80 for evaluating the ground resistance of the grounding grid depends on the size of the grid and the variation of the soil resistivity with the depth.[1]. Use of the resistivity obtained with Wenner's four probe method for a fixed spacing of the probes can be good only for limited cases and will not give correct results in all practical situations.

2. When the resistivity of the top layer of the soil is less than the lower layer,
(a) the factor $K_m K_i$ may be more than 2.5.
(b) the distance to the remote ground will be much more than the distance indicated in the paper.[2,3].

The results of the paper may be applicable only to the limited cases where the values of the various parameters are within the range of the parameters at the substations, using which as the test data, the simplifications have been suggested. The range of variation of all the parameters is not given in the paper. In absence of this information the paper tends to leave an impression that the simplifications suggested in the paper are applicable in all situations. This is not correct. To ensure that the information given in the paper is used only for appropriate cases the authors may give in detail the range of variation of all the critical parameters at the stations where the tests were conducted.

The tolerable step voltage suggested by the authors is five times of that recommended in IEEE Standard 80. This appears to be arbitrary. The authors may give the justification for adopting this value.

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Manuscript received February 28, 1990.

N. BARBEITO and J. LAZZARA: The authors would like to thank the discussers for their interest in the paper and their pertinent comments and questions.

Dr. Dawalibi, Dr. Thapar and Mr. Balakrishnan raised the concern that the author's proposed simplified method might not work at locations where soil characteristics differ from those addressed in the paper. This is an extremely good point and the authors would like to re-emphasize that our method has only been validated for the conditions stated in the paper and in Reference 2. To date the substation grids tested were at locations where the resistivity value of the top layer is larger than the deeper layers. It is the authors' intent to test for other soil conditions if and when they are encountered. Documented resistivity test data for 80 test sites show them all having higher top layer resistivities.
Regarding the discussers' comment on the selection of the resistivity values to be used in the grid resistance calculations (namely the 5 foot and 50 foot spacings), we offer the following comments: One of the main objectives of the test program was to develop a simplified method to determine the appropriate resistivity values to be used in the IEEE Standard 80 formulas from the Wenner test. During the computational analysis and comparison of calculated vs. measured values the following relationship was noted [2]:

$$GPR = V_2 + V_1$$

Since GPR/Ig = Rg

then, $Rg = V_2/Ig + V_1/Ig$

Therefore: $V_2/Ig = (\rho_2/4)\sqrt{\pi/A}$ and $V_1/Ig = \rho_1/L$

Where: GPR = Measured grid potential rise, volts
V_1 = Lowest measured mesh voltage, volts
V_2 = Mesh voltage to remote ground, $(GPR-V_1)$, volts
Ig= Grid test current, amps
ρ_1 = Resistivity of top layer, ohm-m
ρ_2 = Resistivity of lower layer, ohm-m
A = Grid area, meters
L = Total grid cond. length, meters

Soil resistivities were computed from the above relationships and the results compared to the values obtained with the Wenner method. The following are examples of the calculations performed for three of the substations tested (Additional field test data is provided at the end of the discussion):

Peeples Rd. $\rho_2 = (6 \times 4)/(2.9 \times \sqrt{\pi/1564})$
= 184 ohm-m
Wenner's method = 166 ohm-m
Percent difference = 11 %

$\rho_1 = (1.4 / 2.9) \times 1086$ = 524 ohm-m
Wenner's method = 700 ohm-m
Percent difference = 33 %

Belleview $\rho_2 = (12.6 \times 4)/(1.95 \times \sqrt{\pi/4960})$
= 1026 ohm-m
Wenner's method = 900 ohm-m
Percent difference = 14%

$\rho_1 = (2.4 / 1.95) \times 3354$ = 4128 ohm-m
Wenner's method = 4540 ohm-m
Percent difference = 10%

Bayridge $\rho_2 = (1.8 / 0.57) \times 901$ = 2845 ohm-m
Wenner's method = 2942 ohm-m
Percent difference = 3%

With the exception of the top layer value calculated for Peeples Rd., the maximum percent difference found for all the sites tested was 14%. The 33% differential found at Peeples Rd. Substation was attributed to the fact that resistivity tests were performed at a different date than the grid voltage tests and hence under different soil moisture conditions.

Concerning Dr. Thapar's and Mr. Balakrishnan's comments regarding the use of five (5) times the tolerable step voltage recommended in the IEEE Standard 80, we offer the following response. The IEEE Standard 80 indicates that humans can tolerate higher foot-foot voltages than hand to foot or hand to hand voltages. It states 25 times higher. This is based on test results which indicates that a much larger voltage, applied foot to foot, is required to produce the same amount of current in the heart region than for the touch voltage conditions.
Inside the substation grid area, if the touch potential criteria is met so will the step voltage requirement.

The authors' main concern is the step voltage on the virgin soil just outside the grid area. For this condition, with the calculations of tolerable voltages inside the substation being based on surface rock material, it is possible to have slightly higher than tolerable step voltages (as calculated in Reference 1) in the soil area. The arbitrary value of 5 times of that calculated with the formula provided in Reference 1 was selected with the knowledge that it is still a conservative value but it minimizes the requirement for additional grounding for a condition that is already safe.

Mr. Fortin's questions will be answered in the order received.

1) The combined parallel resistance of the ground rods are introduced in the calculations as parallel resistance to the substation ground grid and the external resistance of the transmission OHG's and distribution neutrals. For the example in Appendix I, the introduction of ten ground rods resulted in a grid current value of 12 % of the available phase to ground current for the initial conditions and 6 % for the ultimate lay-out.

2) The typical top layer soil resistivity found in our service area is higher than 1000 ohm-meter. This requires the designer to pay particular attention to the conditions outside the substation fenced area. It is our practice to ground the fence and run a perimeter ground wire 3 to 5 feet outside of it. In addition, the rock layer is extended to this area.

3) The assigned value of 2 ohms to remote ground for each neutral and OHG, is based on field test findings and results of calculated values using the method provided in Reference 3.
In addition, calculations comparing the effect of different combinations of external grounds on current division were made and the results compared to the values obtained from the curves in Reference 7. Note that "Rtd" is the total parallel resistance to remote ground of all the neutrals and transmission grounds connected to the grid.

4) The following illustrates a comparison of calculated vs tested values of grid resistance and the effect of external grounds (no ground rods):
Peeples Rd. Substation

Grid resistance (isolated):

Measured	Calculated
2.3 ohms	2.5 ohms

Grid with 1 neutral & 1 ohg:

Measured	Calculated
0.68 ohms	0.71 ohms

Belleview

Grid resistance (isolated):

Measured	Calculated
7.3 ohms	7.0 ohms

Grid with 2 neutrals & 1 ohg:

Measured	Calculated
0.60 ohms	0.58 ohms

The following is a list of the pertinent parameters for two of the substations tested.

Peeples Rd. Substation

Ground Grid size	110 x 150 ft
Mesh size	10 ft x 10 ft
Grid wire size	0.5 inches (4/0)
Grid depth	18 inches
Soil Resistivity	ρ_1 = 700 Ω-m ρ_2 = 166 Ω-m
Test current, Ig	2.9 amps
Maximum mesh voltage	2.7 volts

Minimum mesh voltage, V_1	1.4 volts
Mesh voltage to remote ground, V_2	6.0 volts
Grid Potential Rise	7.4 volts

Belleview Substation

Ground grid size	262 x 202 ft
Mesh size	10 ft x 10 ft
Grid wire size	0.5 inches (4/0)
Grid depth	18 inches
Soil resistivity	ρ_1 = 4540 Ω-m ρ_2 = 900 Ω-m
Test current, Ig	1.95 amps
Maximum mesh voltage	6.2 volts
Minimum mesh voltage, V_1	2.4 volts
Mesh voltage to remote ground, V_2	12.6 volts
Grid potential rise	15.0 volts

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