The Neutral-to-Earth Voltage (NEV) Test Case and Distribution System Analysis

Wesley G. Sunderman, *Member, IEEE*, Roger C. Dugan, *Fellow, IEEE, and Douglas S. Dorr, Senior Member, IEEE*

***Abstract*-- Modeling NEV issues requires the most detailed circuit models for distribution system analysis except for, perhaps, lightning surge protection analysis. A proposed line model benchmark is solved and results reported. Modeling NEV will become an increasingly important problem. Based on the proliferation of harmonic producing loads in residential environments, the amount of triplen harmonics will tend to increase, with an accompanying increase in neutral-earth voltages.**

***Index Terms*—Stray voltage, Power Distribution System Analysis**

I. Introduction

THIS panel summary describes experience with solving the test case for line models for neutral-to-earth voltage (NEV) analysis of 4-wire multi-grounded neutral distribution systems proposed by Kersting for this panel.[1] This is one of two NEV test feeder models under consideration by the Radial Test Feeders Task Force of the Distribution System Analysis Subcommittee of the Power Systems Analysis, Computing, and Economics (PSACE) Committee. A more complex system was proposed previously and modeled by Penido, et. al.[2] It primarily tests the capability of a distribution system analysis tool to represent complex circuit descriptions and it will continue to be developed. The test feeder explored here is intended to provide a benchmark for one element required for NEV analysis: the multi-phase line model with pole grounds explicitly modeled.

Elevated neutral-to-earth voltage and the subsequent contact voltage potentials that may appear at human and animal contact locations are areas of subjective interpretation for utilities, regulators, and the public. NEV-related issues range from nuisance shocking concerns at swimming pools, hot tubs and water faucets to outdoor showers, boat docks and animal contact points. Along with the traditional power frequency related (50/60 Hz) NEV, other line-connected equipment such power line carrier-based communications devices as well as harmonic-generating variable speed drives, personal computers, and residential appliances have been found to contribute to elevated NEV and subsequent contact voltage potentials[3].

There has been substantial interest within the IEEE Power Engineering Society - for example, the IEEE P1695 "Working Group on Voltages at Publicly and Privately Accessible Locations" – and within the power industry as a whole, regarding how to properly evaluate and address NEV related concerns. The requirements include a need for systematic research into areas of interest that include:

- measurement procedures,
- sensitivity to touch voltages,
- effects of grounding configurations,
- field testing of mitigation techniques, and
- the subject of this paper – modeling and simulation of the NEV phenomena at distribution grounding points and at human and animal contact points.

A major challenge in developing accurate contact voltage models is the extreme variability in modeled parameters – such as resistances, connection impedances, and circuit loading – as well as the need to confirm the model with actual field measurements. Since the contact voltage level can change as circuit loading, load balance, and other variables change, it is difficult to obtain accuracies better than ±10% without limiting the flexibility of the model when evaluating multiple points on a single circuit or multiple circuits out of the same substation[4]. Therefore, users of the results need to take this into consideration when making decisions that will require costly changes to a distribution system.

Accurate NEV models will provide the industry with credible and objective methodologies and information to; first enable more informed decisions on quantifying NEV related concerns, and to secondly, understand the range of options that will effectively deal with each concern. The key is to clearly understand the impacts on NEV and contact voltage levels that may be observed by varying parameters such as neutral conductor size, ground resistance, load balancing, and better grounding/bonding techniques. Investigators can then compare relative reductions in voltage levels versus the costs to implement each option.

II. Test Case Description

The test case studied for this paper is shown in Fig. 1. It consists of a 20-section 3-phase, 4-wire line connected between an ideal source and three single-phase unbalanced

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loads specified by their real and reactive power components.

A. Circuit

The circuit under consideration is shown conceptually in Fig. 1. The source is an ideal grounded-wye source, rated at 12.47 kV (line-line). From the source, three phase conductors and a neutral conductor are connected to poles at every 300 feet. The line geometry is defined in Fig. 2.

At each of the poles, the neutral conductor is grounded through a 100 ohm resistance. The total length for the line is 6,000 feet.

At the end of the line three single-phase loads are connected line-neutral, consisting of:

Phase a: 3000 kVA at 0.90 lagging power factor
Phase b: 3500 kVA at 0.95 lagging power factor
Phase c: 2500 kVA at 0.85 lagging power factor

The analysis for the test circuit includes determining the:

- equivalent phase impedance matrix from the source to the load
- line-to-neutral voltages at the load
- line-to-ground voltages at the load
- load currents
- neutral current
- ground current
- neutral-earth voltages (NEV)

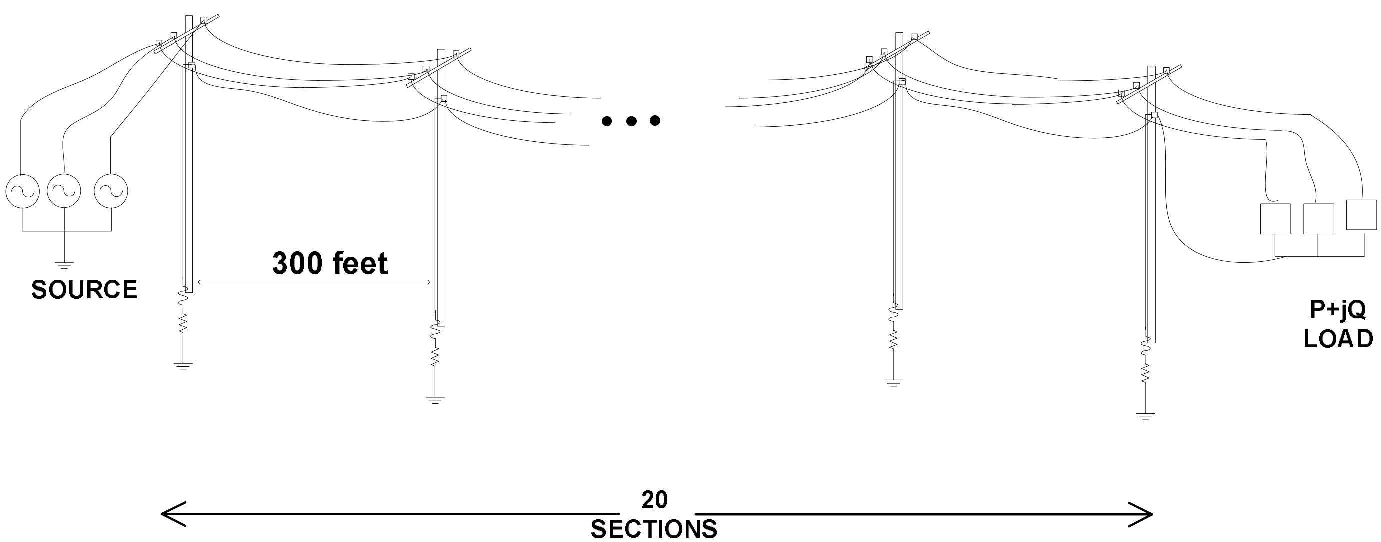

Fig. 1. NEV Line Model Benchmark Test Circuit.

B. Line Geometry

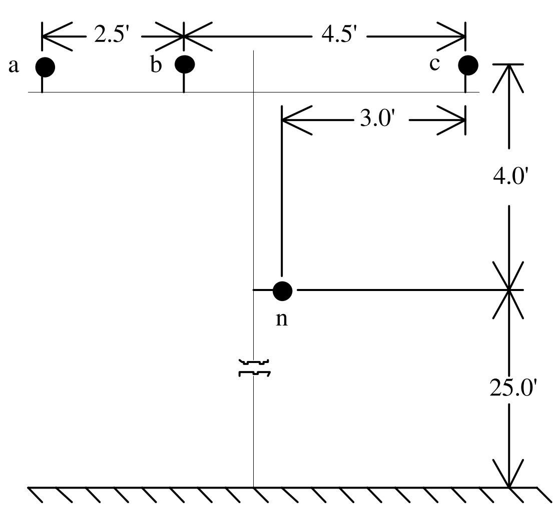

Fig. 2. Line Geometry for NEV Test Feeder

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III. Solving the Test Case

With EPRI's Distribution System Simulator (DSS) the solution was obtained without difficulty in a straightforward manner. The line impedance was defined by entering the geometry. The line impedance matrices were computed by conventional line constants methods yielding the values given in the Appendix. Each pole span was modeled as a separate line section and the 100-ohm grounding resistance was modeled by connecting a single-phase reactor (impedance = 100 + j0) between the neutral conductor and ground (zero-voltage reference).

As seen in Table I, the power flow solution converged in 4 iterations; the test case is not difficult to solve once the model is constructed. The model consisted of a total of 83 nodes at which voltages were computed, divided among 20 4-node buses and one 3-node bus (the source). There were 20 4-

conductor line sections, 20 single-phase reactor models representing the pole down leads and grounding resistances, 3 single-phase loads, and one 3-phase voltage source – for a total of 44 devices in the circuit model. (see Table I)

TABLE I
60 HZ POWER FLOW SUMMARY

```
Status = SOLVED
Devices = 44
Buses = 21
Nodes = 83
Total Iterations = 4
```

The circuit was solved at both 60 Hz and 180 Hz.

A. 60 Hz Solution

The next three figures show the results computed for the 60Hz solution. The NEV increases linearly from zero at the source (not shown) to nearly 160V at bus 20, the load site. This voltage is due to the unbalanced load current that flows in the neutral and ground paths. Fig. 4 and Fig. 5 show how the currents split between the earth and neutral conductor along the line.

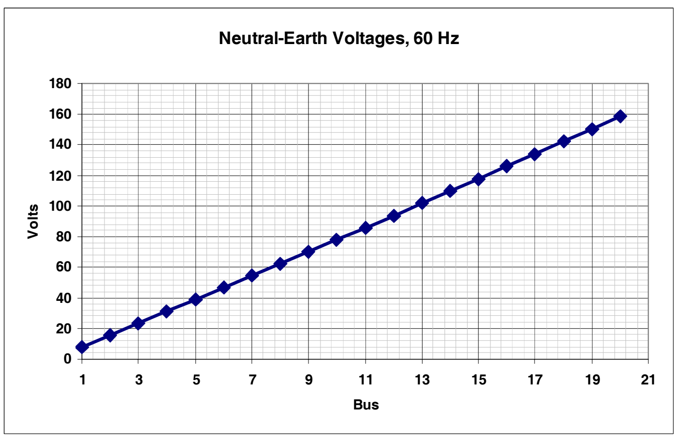

Fig. 3 Neutral-to-Earth Voltages Computed at each Bus, 60 Hz.

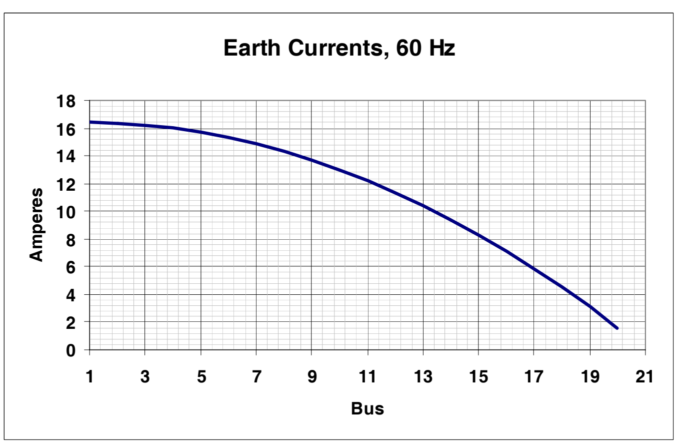

Fig. 4. Currents flowing in the Earth at Each Bus, 60 Hz

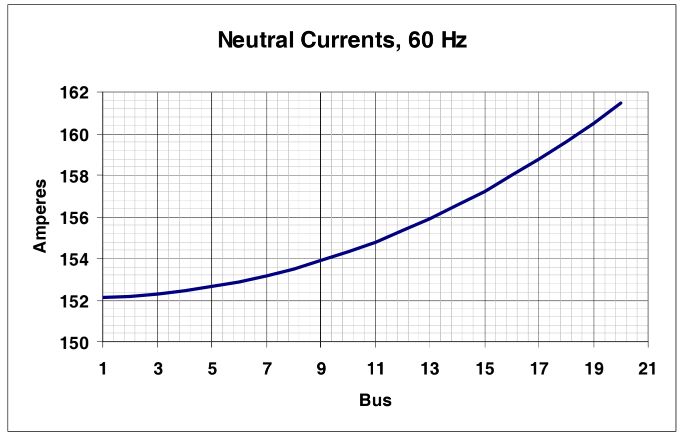

Fig. 5. Currents Flowing in the Neutral Wire at each Bus, 60 Hz

1) Losses at 60 Hz

The total losses computed at 60 Hz for the problem as specified in [1] is 215.5 kW. This represents 2.64% of the load. The bulk of these losses are simply due to I^2R losses in the phase conductors to supply the load. This will become apparent when we compare with the losses at 180 Hz below. However, no attempt has been made to assign the losses to the various conducting paths.

2) Short Circuit Impedance Matrix

Table II shows the short circuit impedance matrix computed by our computer program for bus 20, the load site, at 60 Hz. This is a 4x4 matrix with the neutral explicitly modeled and is intended to include the effect of all the pole grounding resistances.

TABLE II
SHORT CIRCUIT IMPEDANCE MATRIX AT LOAD SITE
OHMS AT 60 HZ

0.51969+j1.62330,	0.16603+j 0.94863,	0.15620+j 0.81618,	0.19060+j 0.85157
0.16603+j 0.94863,	0.52875+j1.62070,	0.16073+j 0.87372,	0.19213+j 0.89059
0.15620+j0.81618,	0.16073+j0.87372,	0.51436+j1.62910,	0.19757+j0.85229
0.19060+j0.85157,	0.19213+j0.89059,	0.19757+j0.85229,	0.83992+j1.42990

3) Voltages at the load

Table III and Table IV show the voltages computed from line-to-ground and from line-to-neutral at the load site, respectively. The voltages in Table IV represent the voltages seen by the load, which is assumed to be connected line-to-neutral at bus 20 (see Fig. 1). The neutral shifts about 2.2% in this case.

TABLE III
LINE-TO-GROUND VOLTAGES AT THE LOAD
60 HZ

Phase	|V|, kV	Angle	Per unit
a	6.8465	-1.8	0.95093
b	6.9383	-122.5	0.96369
c	6.9602	118.5	0.96672
n	0.15888	-33.5	0.022067

TABLE IV
LINE-TO-NEUTRAL VOLTAGES AT THE LOAD
60 HZ

Phase	|V|, kV	Angle	Per Unit
a	6711.722	-1.1218	0.932184
b	6937.434	-123.809	0.963532
c	7100.816	119.1192	0.986224

B. 180 Hz Solution

Although the test case described in [1] defines only 60 Hz parameters, we know from experience that NEV issues generally involve triplen harmonics, notably the 3rd harmonic, or 180 Hz in this case. Fig. 6 shows a typical measurement where the NEV is nearly equal parts 60 Hz and 180 Hz. Therefore, the NEV test case solution was repeated at 180 Hz.

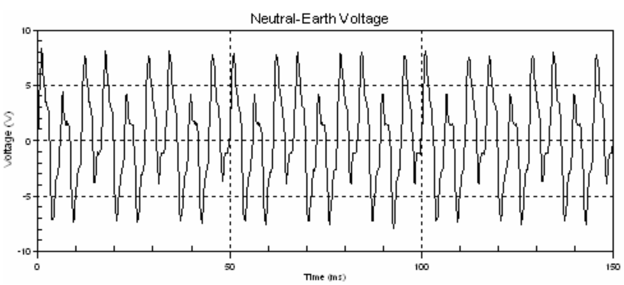

Fig. 6. Neutral-earth voltage measured at a pole ground in North America

For this demonstration, each phase of the load current on the test case distribution feeder was assumed to have a 3rd harmonic content of 8%. The computer program is set up to automatically compute the harmonic currents from the fundamental frequency solution when solving in harmonics solution mode. Thus, immediately after the 60 Hz values shown above were computed, the values shown in the next three figures were computed following typical practice for harmonic analysis. The 3rd harmonic currents were assumed to be exactly in phase with each other. The utility source was assumed to contribute no distortion.

The NEVs at 180 Hz (Fig. 7) and the earth currents at 180 Hz (Fig. 8) are similar to the same values at 60 Hz for this case. The neutral currents (Fig. 9) are much lower than the 60 Hz neutral currents.

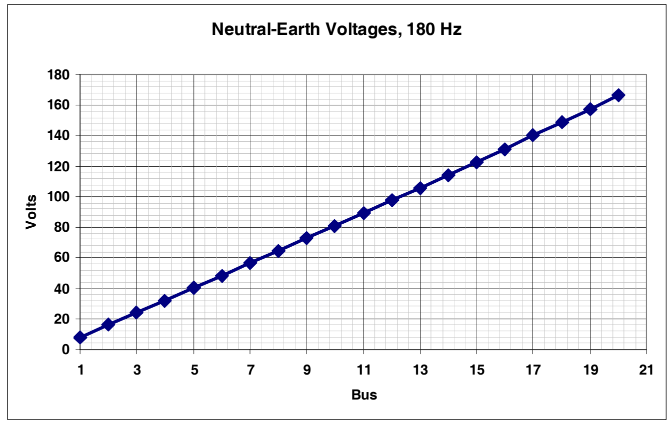

Fig. 7 Neutral-to-Earth Voltages Computed at each Bus, 180 Hz.

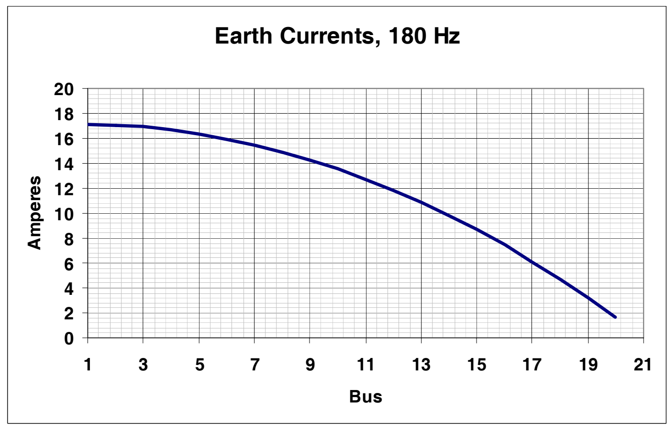

Fig. 8. Currents flowing in the Earth at Each Bus,180 Hz

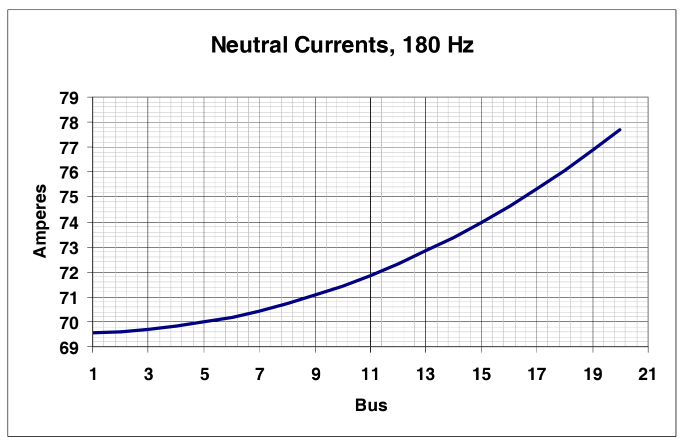

Fig. 9. Currents Flowing in the Neutral Wire at each Bus, 180 Hz

1) Losses at 180 Hz

The total losses computed at 180 Hz for this problem are 6.2 kW, which is considerably less than the 215 kW for the 60 Hz component of the current. This is expected because the phase currents are much lower.

IV. THE BENCHMARK VS. REALITY

The authors have studied several neutral-earth voltage cases in North America. The observed conditions have been successfully modeled and solutions have been developed and implemented. While the proposed test case for the line model is an important benchmark for a component of the system model, one must keep in mind that the line is only one component of the model.

A number of the cases investigated to date have involved distributed harmonic loads. In one instance, the neutral-earth voltage issues were found to be attributed to distributed residential harmonic loads. While in another case, the neutral-earth voltage issues were found to be due to a large number of three-phase adjustable-speed drives, connected in single-phase configurations.

One way in which these cases differ from the test case is that they typically involve the modeling of several thousand nodes. They also include distributed harmonic loads that have predominantly 3rd harmonic content. An example neutral-earth voltage waveform measured at a pole ground is shown in Fig. 6.

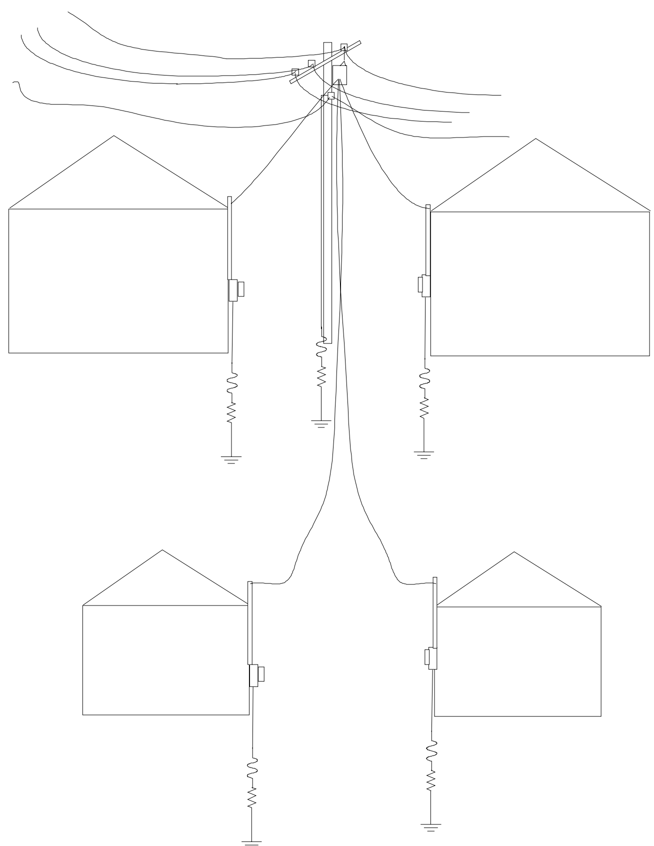

Fig. 10. Neutral-ground Connections for Typical Residential Service

Additionally, the cases involve modeling a number of other utility and customer ground rods, in addition to the electric utility pole grounds. Fig. 10 illustrates multiple grounding electrodes at a single pole-top residential service transformer serving four homes. Since all the neutral conductors are connected together, the multiple grounding points disperses the current, effectively lowering the apparent grounding resistance. Thus, the NEV predicted in detailed feeder models is much less than the test benchmark yields.

The voltages of interest are the NEV appearing at the customer's facilities. Therefore, at least a few representative models of the secondary circuits must be constructed. Grounded conductors from other nearby utilities, such as cable TV and telephone must sometimes be modeled if measurements indicate problems with these services. The purpose of building the models is to evaluate how well proposed solutions such as filters or improving certain ground electrodes might work.

NEV problems can be accentuated by resonance issues with grounded-wye capacitors on the feeder that alter the impedance of the zero-sequence circuit. Thus, it is important to represent all feeder capacitors, cable capacitance, and larger customer capacitors that affect the zero sequence of the distribution system..

V. Conclusions

This paper has provided results from the proposed line model benchmark for explicitly including pole ground resistances. Other details relevant to NEV modeling are presented.

Modeling NEV will become an increasingly important problem. Based on the proliferation of harmonic producing loads in residential environments, the amount of triplen harmonics (which are non-canceling), will tend to increase, with a corresponding increase in neutral-earth voltages

NEV analysis requires one of the most detailed circuit models for distribution system analysis except for, perhaps, lightning surge protection analysis like that needed for the problems described in [5]. Evolving distribution system analysis tools so that they can handle the NEV problem is encouraged. This must be accompanied by a complementary evolution of data models capable of providing sufficient detail. This paper represents a first step in the process of adding the appropriate capability.

To properly analyze the NEV problem, tools must be capable of:

- Representing large sets of coupled conductors,
- Representing multiple circuits and shared rights of way,
- Modeling the connections to earth, including at customer services,
- Solving the system at both fundamental power frequency and at least the 3rd harmonic.

While tools with these features may seem unimaginable to many readers, the authors have observed that many utilities already collect data on customer services in their GIS databases that is nearly sufficient to perform NEV analysis. Grounding resistances will differ at each location and will also vary by time of year. An area for research is to find ways to deal with this uncertainty in ground resistance values.

VI. Appendix

Line Impedances @ 60 Hz
(4x4 matrices, lower triangle form)
Order of Phases: abcn (see Fig. 2)

```
R MATRIX, ohms per km
0.245256
0.0582057 0.245256
0.0582055 0.0582056 0.245256,
0.0582745 0.0582746 0.0582745 0.419321

jX MATRIX, ohms per km
0.885027
0.535973 0.885027,
0.458342 0.491655 0.885027,
0.474334 0.495505 0.483641 0.967657,

Susceptance (jB) MATRIX, S per km
3.52623E-6
-1.14173E-6 3.71665E-6
-4.37331E-7 -7.26846E-7 3.35207E-6
-5.25407E-7 -6.68079E-7 -6.71857E-7 3.32103E-6
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VII. References

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VIII. Biographies

Wesley G. Sunderman (M'1991) is a Sr. Power System Engineer for EPRI in Knoxville, TN. He received his Bachelor's degree from, John Brown University (1991).

From 1997 to 2000 he served as Power Quality Engineer at Square D Company in LaVergne, TN. From 1991 to 1997 he held various positions at Southwestern Electric Power Company in Shreveport, LA.

Roger C. Dugan (M'74–SM'81–F''00) is Sr. Technical Executive for EPRI in Knoxville, TN. He holds the BSEE degree from Ohio University, Athens, OH (1972) and the MEEPE degree from Rensselaer Polytechnic Institute, Troy, NY (1973).

From 1992-2004, he served as Sr. Consultant for Electrotek Concepts, Knoxville, TN. From 1973 – 1992 he held various positions in the Systems Engineering department of Cooper Power Systems in Canonsburg, PA and Franksville, WI. Roger has worked on many diverse aspects of power engineering over his career because of his interests in applying computer methods to power system simulation. The focus of his career has been on utility distribution systems. He has been particularly active in developing advanced methods for distribution system analysis. He was elected a IEEE Fellow in 2000 for his contributions in harmonics and transients analysis. He is coauthor of Electrical Power Systems Quality published by McGraw-Hill, 2nd edition. He is currently Chair of the IEEE PES Power Systems Analysis, Computing, and Economics Committee. He was the 2005 recipient if the IEEE Excellence in Distribution Engineering Award.

Douglas S. Dorr (M'1992, SM'2004) is a project manager with EPRI. He holds the Bachelor of Science degree in Engineering from Indiana Institute of Technology in Fort Wayne, Indiana (1989). Mr. Dorr manages and supports many of the EPRI research initiatives surrounding elevated neutral to earth voltage and urban stray voltage. He has been involved with power quality and distributed generation projects for the past 15 years including power conditioning device testing/application, surge/lightning protection, and monitoring/field demonstration of distributed resources. Mr. Dorr Chaired the 2005 revision of the IEEE Emerald Book, is the 2006-08 Chair of the IEEE Surge Protective Devices Committee and is a member of the IEEE 1695 Working Group on Voltages at Publicly and Privately Accessible Locations. He has authored over 50 technical publications in the above mentioned research areas.