A Test Case for the Calculation of Geomagnetically Induced Currents

Article *in* IEEE Transactions on Power Delivery · October 2012

DOI: 10.1109/TPWRD.2012.2206407

David Boteler
Natural Resources Canada

Risto Pirjola
Finnish Meteorological Institute

A Test Case for the Calculation of Geomagnetically Induced Currents

Randy Horton, *Senior Member, IEEE*, David Boteler, *Senior Member, IEEE*, Thomas J. Overbye, *Fellow, IEEE*, Risto Pirjola, and Roger C. Dugan, *Fellow, IEEE*

***Abstract*—Geomagnetically induced currents (GICs) in power systems can be attributed to problems ranging from transformer overheating, misoperation of protective relays, and voltage instability. The assessment of the geomagnetic hazard to power systems requires accurate modeling of the GICs that are expected to occur. However, to date, there are no publicly available test cases to validate software programs used to compute GIC. The following paper presents a hypothetical network that can be used as a test case for validating results from GIC modeling software. The network contains many features found in real networks such as: different voltage levels, two- and three-winding transformers and autotransformers, multiple transmission lines in the same corridorn and GIC blocking devices. GIC is calculated in the network for two geoelectric field scenarios: a 1 V/km uniform Northward electric field and a 1 V/km uniform Eastward electric field. Detailed simulation results and corresponding input data are provided for each of the two scenarios. Simulation results that are provided have been validated using four independent GIC modeling programs.**

***Index Terms*—Geomagnetically induced currents (GICs), power system analysis.**

I. Introduction

DURING geomagnetic disturbances, magnetic-field variations drive low-frequency electric currents along transmission lines and through transformer windings to ground. These geomagnetically induced currents (GICs) produce half-cycle saturation of transformers leading to harmonic generation and increased reactive power demand that can cause misoperation of protective relays and impact system stability [1]–[7].

As part of assessing the performance of power systems subjected to geomagnetic disturbances (GMDs), it is necessary to model the GIC produced by different levels of geomagnetic activity. A variety of GIC modeling software has been developed; however, for the modeling results from these routines to be used with confidence it is necessary to know that they give consistent results. Unlike other power system computations (e.g., distribution system analysis), which have test cases to validate software [8], no IEEE test case exists to validate GIC modeling software. To facilitate the testing and comparison of GIC modeling procedures, a benchmark test case is presented. The details of the test case are designed to 1) include many features found in typical high voltage (HV) and extra high voltage (EHV) networks, and 2) show the results obtained with four independent software programs. To aid those involved in the software validation process, the values obtained at key points in the calculation process are also presented.

Manuscript received March 21, 2012; accepted June 12, 2012. Date of publication September 11, 2012; date of current version September 19, 2012. This work was supported in part by the North American Reliability Corporation (NERC), in part by the Electric Power Research Institute, and in part by the Natural Resources Canada in the development of the GIC test case. Paper no. TPWRD-00300-2012.

R. Horton and R. C. Dugan are with the Electric Power Research Institute, Knoxville, TN 37932 USA (e-mail: rhorton@epri.com; rdugan@epri.com).

D. Boteler is with Natural Resources Canada, Ottawa, ON KIA 0Y3 Canada (e-mail: dboteler@nrcan.gc.ca).

R. Pirjola is with the Finnish Meteorological Institute, Helsinki, Finland (e-mail: Risto.Pirjola@fmi.fi).

T. J. Overbye is with the University of Illinois at Urbana-Champaign, Urbana-Champaign, IL 61801 USA (e-mail: overbye@illinois.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRD.2012.2206407

II. Test Case Specifications

The test case represents a hypothetical 20 bus EHV network consisting of 500 kV and 345 kV lines and transformers. Fig. 1 shows a single-line diagram of the network. The network includes single transmission lines as well as some that occupy the same transmission corridor. In a couple of areas, the path taken by the transmission lines intersects with the path taken by other transmission lines. The substations feature both conventional transformers and autotransformers. Also included are series and neutral connected GIC blocking devices.

To specify a network for modeling GIC requires three sets of data: substation, transmission lines, and transformers. These data are provided in the following sections.

A. Substation Data

Substation locations (latitude and longitude) and resistance to remote earth of the substation ground grid are provided in Table I. A geographical view of the single line diagram is provided in Fig. 2.

B. Transmission Line Data

The 500 kV lines indicated in Fig. 1 are comprised of (3) bundled 1351 ACSR conductors per phase corresponding to a dc resistance of 0.0227 Ω/mi. The 345 kV lines are comprised of (2) bundled 1033 ACSR conductors per phase with an equivalent dc resistance of 0.0455 Ω/mi. In practice, line lengths are obtained from survey data, and because they do not follow a direct path between substations, they are slightly longer than the direct point-to-point distance between substations. For the test case, the line lengths shown in Table II have been increased by 3% to account for the difference between the actual line length and the straight-line distance between substations and line sag. The capacitance of series blocking capacitors is 10 μF.

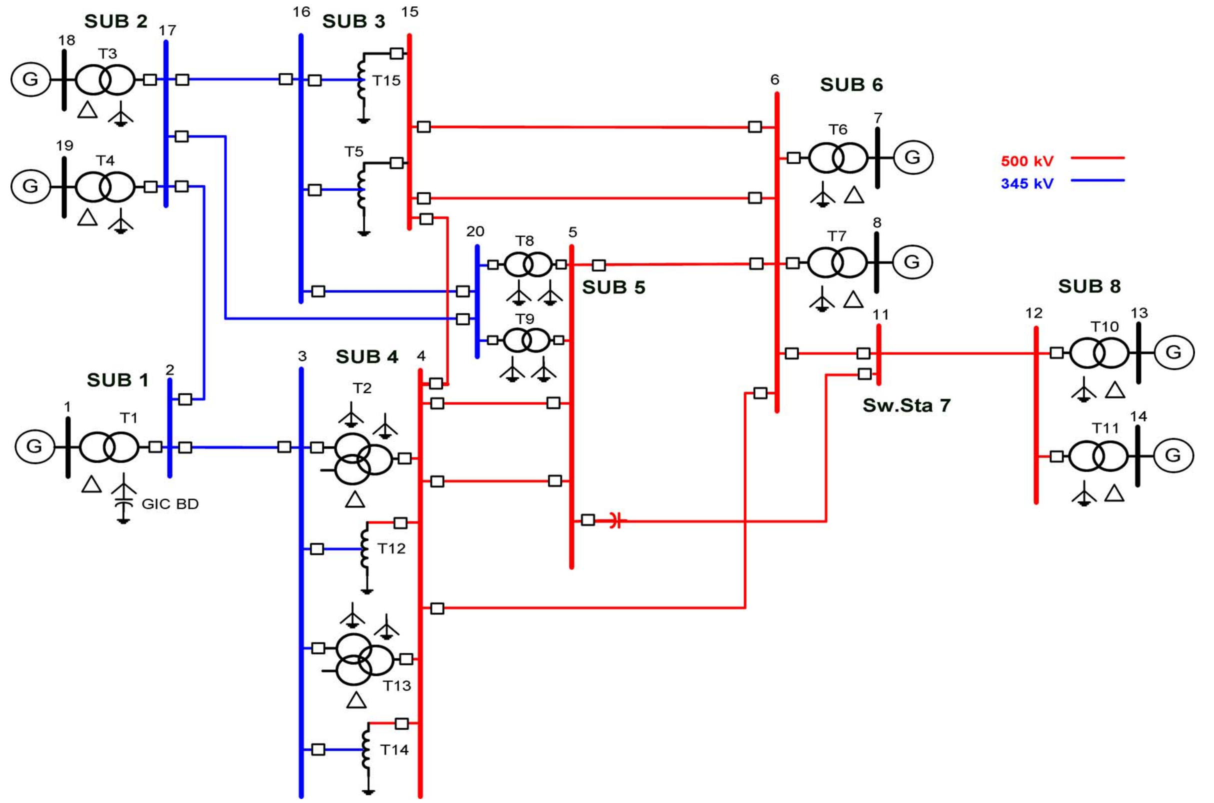

Fig. 1. Single-line diagram of benchmark test case.

C. Transformers

Information for the transformers indicated in Fig. 1 is provided in Table III. Note that W1 and W2 represent the resistance of HV and LV windings, respectively for transformers, and the series and common windings, respectively for autotransformers. Delta windings are shown in the single-line diagram for completeness, but they do not provide a path for GIC and are not considered when calculating GIC. Thus, their resistance values are provided as N/A. A GIC blocking device (BD), consisting of a 10 μF capacitor, is installed in the neutral-ground connection of transformer T1.

III. CALCULATION PROCEDURE

The following sections provide an overview of the modeling procedure for determining GIC in HV and EHV networks.

A. Calculation of Input Voltages

The induced voltage (= voltage source) in the transmission line between stations A and B is computed by integrating the geoelectric field along the route of the line

$$V = \oint_R \vec{E} \circ d\vec{l} \tag{1}$$

where $\vec{E}$ is the electric field vector at the location of the transmission line, the route of the line between stations A and B (i.e., the integration path) is denoted by R, and $d\vec{l}$ is the incremental line segment length including direction. If the geoelectric field is assumed constant in the geographical area of a transmission line, then only the coordinates of the end points of the line are important, regardless of routing twists and turns. The resulting incremental length vector $d\vec{l}$, becomes $\vec{L}$. The vector $\vec{L}$, representing the length and direction of the line between end points, can be constructed by using an arbitrary reference; however, such a method can introduce error. An improved method is to compute the distances in the NS and EW directions independently (see the Appendix). Then, the input voltages are given by

$$V = E_N L_N + E_E L_E \tag{2}$$

where E_N is the Northward electric field (V/km), E_E is the Eastward electric field (V/km), L_N is the Northward distance (km), and L_E is the Eastward distance (km).

B. Network Analysis

The voltage sources from Section III-A are used as input to a dc model of the network constructed using the resistances in Tables I–III. The resulting dc network can be solved using standard circuit analysis techniques. The nodal admittance method is usually preferred because of its greater computational efficiency, and was the method used to obtain the results shown here. Even with the same basic approach, there can be different software implementations. The results presented here have been calculated using four different sets of software that have been independently produced by different coauthors of this paper.

IV. BENCHMARK SIMULATION RESULTS

The benchmark test case described in Figs. 1 and 2 and Tables I–III was evaluated against two electric field scenarios:

1) uniform E field, 1 V/km, Northward;
2) uniform E field, 1 V/km, Eastward.

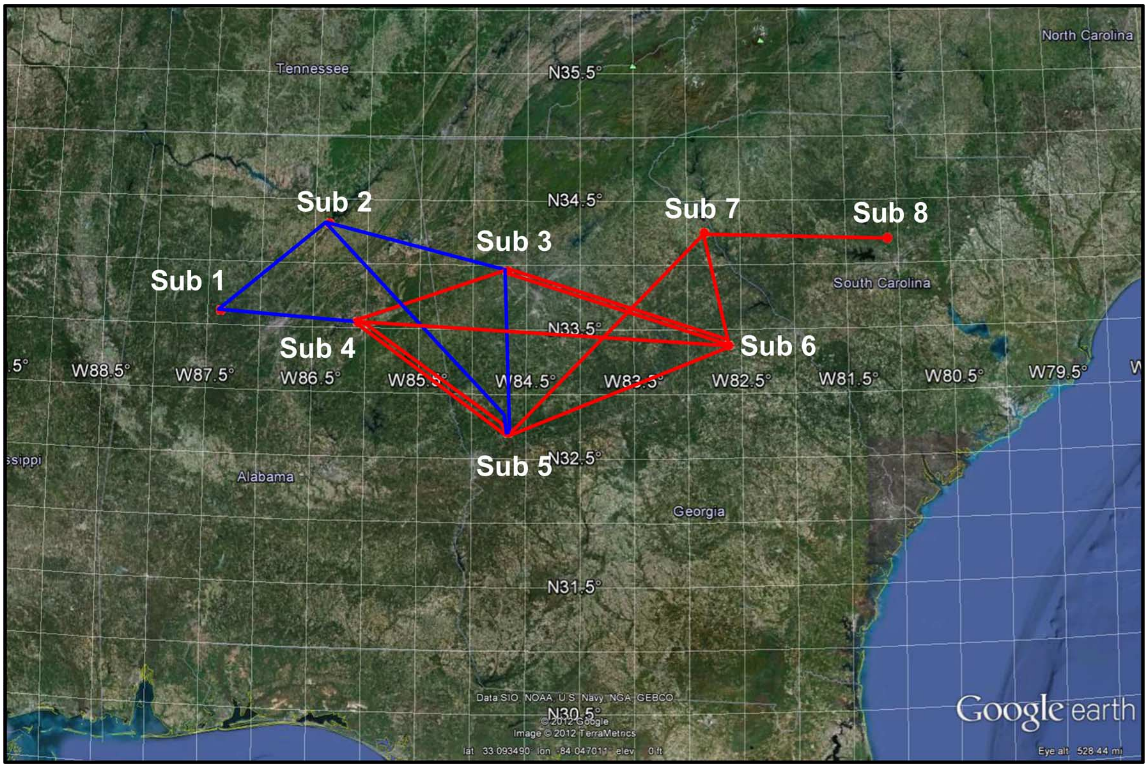

Fig. 2. Single-line diagram of benchmark test case (geographical view).

TABLE I
SUBSTATION LOCATION AND GRID RESISTANCE INFORMATION

Name	Latitude	Longitude	Grounding Resistance (Ohm)
Sub 1	33.6135	-87.3737	0.2
Sub 2	34.3104	-86.3658	0.2
Sub 3	33.9551	-84.6794	0.2
Sub 4	33.5479	-86.0746	1.0
Sub 5	32.7051	-84.6634	0.1
Sub 6	33.3773	-82.6188	0.1
Sub 7	34.2522	-82.8363	N/A
Sub 8	34.1956	-81.0980	0.1

TABLE II
TRANSMISSION LINE INFORMATION

Line	From Bus	To Bus	Voltage (kV-LL)	Length (miles)	Resistance (ohm/phase)
1	2	3	345	77.18	3.512
2	2	17	345	77.47	3.525
3	15	4	500	87.51	1.986
4	17	16	345	102.54	4.665
5	4	5	500	103.31	2.345
6	4	5	500	103.31	2.345
7	5	6	500	131.05	2.975
8	5	11	500	154.57	3.509
9	6	11	500	63.59	1.444
10	4	6	500	205.57	4.666
11	15	6	500	128.81	2.924
12	15	6	500	128.81	2.924
13	11	12	500	102.39	2.324
14	16	20	345	88.98	4.049
15	17	20	345	152.53	6.940

TABLE III
TRANSFORMER DATA

Name	Type	Resistance W1 (Ohms/phase)	Bus No.	Resistance W2 (Ohms/phase)	Bus No.
T1	GSU w/ GIC BD	0.1	2	N/A	1
T2	GY-GY-D	0.2	4	0.1	3
T3	GSU	0.1	17	N/A	18
T4	GSU	0.1	17	N/A	19
T5	Auto	0.04	16	0.06	15
T6	GSU	0.15	6	N/A	7
T7	GSU	0.15	6	N/A	8
T8	GY-GY	0.04	5	0.06	20
T9	GY-GY	0.04	5	0.06	20
T10	GSU	0.1	12	N/A	13
T11	GSU	0.1	12	N/A	14
T12	Auto	0.04	4	0.06	3
T13	GY-GY-D	0.2	4	0.1	3
T14	Auto	0.04	4	0.06	3
T15	Auto	0.04	15	0.06	16

Along with providing examples of GIC calculations for the test case, these electric fields are specifically chosen because GIC produced by a uniform electric field of any other magnitude or orientation can be obtained by appropriate scaling and addition of the GIC values obtained from these two scenarios [9].

The first step in solving a network for GIC is to calculate the induced voltage in each line by solving (2) using the distances calculated with the formulas presented in the Appendix. The results of these calculations for a Northward and Eastward electric field of 1 V/km are provided in Table IV.

The resulting bus voltages at each substation bus are provided in Table V for both electric field scenarios.

TABLE IV
INPUT VOLTAGES

Line	From Bus	To Bus	Vsource Northward Electric Field (Volts)	Vsource Eastward Electric Field (Volts)
1	2	3	-7.28	120.60
2	2	17	77.31	93.16
3	15	4	-45.16	-129.27
4	17	16	-39.42	155.56
5	4	5	-93.47	131.69
6	4	5	-93.47	131.69
7	5	6	74.56	190.99
8	5	11	171.60	169.82
9	6	11	97.05	-20.14
10	4	6	-18.92	321.26
11	15	6	-64.08	191.11
12	15	6	-64.08	191.11
13	11	12	-6.29	160.17
14	16	20	-138.64	1.49
15	17	20	-178.06	158.17

TABLE V
BUS VOLTAGES

Substation	Bus	Northward Electric Field (volts)	Eastward Electric Field (volts)
1	2	-12.39	-190.04
2	17	25.05	-41.01
3	15	30.09	-24.39
3	16	29.37	-22.99
4	3	20.04	-125.10
4	4	20.33	-125.97
5	5	-29.01	-7.26
5	20	-29.04	-6.13
6	6	-7.16	44.32
7	11	60.57	-40.47
8	12	7.11	15.67

TABLE VI
GIC (A/PHASE) IN TRANSMISSION LINES

Line	From Bus	To Bus	GIC For Northward E Field (Amps/Phase)	GIC For Eastward E Field (Amps/Phase)
1	2	3	-11.31	15.85
2	2	17	11.31	-15.85
3	15	4	-17.83	-13.94
4	17	16	-9.38	29.48
5	4	5	-18.82	5.54
6	4	5	-18.82	5.54
7	5	6	17.72	46.86
8	5	11	0.00	0.00
9	6	11	20.30	44.77
10	4	6	1.84	32.36
11	15	6	-9.17	41.86
12	15	6	-9.17	41.86
13	11	12	20.30	44.77
14	16	20	-19.81	-3.80
15	17	20	-17.86	17.76

Table VI provides the GIC flow in each of the transmission lines resulting from a Northward or Eastward geoelectric field.

TABLE VII
TOTAL GIC FLOW INTO SUBSTATION GROUND GRID

Name	Northward E Field GIC (Amps)	Eastward E Field GIC (Amps)
Sub 1	0.00	0.00
Sub 2	115.63	-189.29
Sub 3	139.85	-109.49
Sub 4	19.98	-124.58
Sub 5	-279.08	-65.46
Sub 6	-57.29	354.52
Sub 7	0.00	0.00
Sub 8	60.90	134.30

TABLE VIII
GIC FLOW IN TRANSFORMER WINDINGS

Transformer	Winding	GIC for Northward E Field (Amps/Phase)	GIC for Eastward E field (Amps/Phase)
T1	HV	0.00	0.00
T2	HV	1.75	-6.94
T2	LV	0.59	-5.18
T3	HV	19.27	-31.55
T4	HV	19.27	-31.55
T5	Series	18.09	-34.89
T5	Common	23.31	-18.25
T6	HV	-9.55	59.09
T7	HV	-9.55	59.09
T8	HV	-27.67	-17.89
T8	LV	-18.84	6.98
T9	HV	-27.67	-17.89
T9	LV	-18.84	6.98
T10	HV	10.15	22.38
T11	HV	10.15	22.38
T12	Series	7.24	-21.75
T12	Common	0.99	-8.64
T13	HV	1.75	-6.94
T13	LV	0.59	-5.18
T14	Series	7.24	-21.75
T14	Common	0.99	-8.64
T15	Series	18.09	-34.89
T15	Common	23.31	-18.25

Table VII provides the total GIC flow (combination of all phases for all transformers) into the substation ground grid resulting from a Northward or Eastward electric field.

The GIC flows that are of concern for power system operation are those in the transformer windings themselves. Table VIII provides the GIC flows in individual transformer windings resulting from a Northward or Eastward geoelectric field. Positive values correspond to GIC flow from the higher voltage node to the lower voltage node or neutral point.

V. CONCLUSION

A hypothetical power network (test case) has been presented that can be used as a test case for GIC modeling. The network was designed to include many features found in real networks: different voltage levels, conventional transformers, and autotransformers, including some connected in parallel, multiple transmission lines in the same corridor and GIC blocking

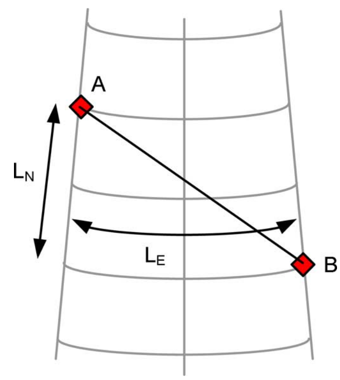

Fig. 3. Substation location coordinates.

TABLE IX
PARAMETERS OF THE WGS84 EARTH MODEL

Parameter	Symbol	Value
Equatorial radius	a	6378.137 km
Polar radius	b	6356.752 km
Eccentricity squared	e^2	0.00669437999014

devices. GIC calculations are performed for two cases: 1) a uniform northward geoelectric field and 2) uniform Eastward geoelectric field, and pertinent calculation results are provided for the validation of GIC calculation software tools.

APPENDIX
CALCULATION OF DISTANCES

Consider a transmission line between substations A and B as shown in Fig. 3. Assuming a spherical earth, the NS distance is simply calculated from the difference in latitude of substations A and B. However, there is no similar simple relationship for the EW distance because, as shown in Fig. 3, lines of longitude converge as they approach the pole. Consequently, it is necessary to take into account the latitude of the substations when converting their longitudinal separation into a distance.

To obtain more accurate values (and to be consistent with substation latitudes and longitudes obtained from GPS measurements), it is even necessary to take into account the nonspherical shape of the Earth [10]. The Earth is an ellipsoid with a smaller radius at the pole than at the equator. The precise values depend of the Earth model used. Here we use the WGS84 model (Table IX) which is used in the GPS system.

The North-South distance is given by

$$L_N = \frac{\pi}{180} M \cdot \Delta \mathrm{lat} \tag{A1}$$

where M is the radius of curvature in the meridian plane and is described by(A2)

$$M = \frac{a(1-e^2)}{(1-e^2 \sin^2 \phi)^{1.5}}. \tag{A2}$$

Substituting in the values from Table IX gives the expression for the Northward distance in kilometers

$$L_N = (111.133 - 0.56 \cos(2\phi)) \cdot \Delta \mathrm{lat} \tag{A3}$$

where $\Delta\,\mathrm{lat}$ is the difference in latitude (degrees) between the two substations A and B, and ϕ is defined in (A4) as the average of the two latitudes

$$\phi = \frac{\mathrm{Lat}A + \mathrm{Lat}B}{2}. \tag{A4}$$

Similarly, the East-West distance is given by

$$L_E = \frac{\pi}{180} N \cos\phi \cdot \Delta \mathrm{long} \tag{A5}$$

where N is the radius of curvature in the plane parallel to the lattitude as defined in (A6) and $\Delta\mathrm{long}$ is the difference in longitude (degrees) between the two substations A and B

$$N = \frac{a}{\sqrt{1-e^2\sin^2\phi}}. \tag{A6}$$

Substituting the values from Table IX gives the following expression for the Eastward distance in kilometers:

$$L_E = (111.5065 - 0.1872 \cos 2\phi) \cdot \cos\phi \cdot \Delta\mathrm{long}. \tag{A7}$$

ACKNOWLEDGMENT

The authors would like to thank the North American Reliability Corporation (NERC), Electric Power Research Institute, and Natural Resources Canada in the development of the GIC test case.

REFERENCES

[1] *Investigation of Geomagnetically Induced Currents in the Proposed Winnipeg–Duluth–Twin Cities 500 kV Transmission Line*. Palo Alto, CA: Elect. Power Res. Inst., Jul. 1981, EPRI EL-1949.
[2] *Solar Magnetic Disturbances/Geomagnetically Induced Current and Protective Relaying*. Palo Alto, CA: Elect. Power Res. Inst., Aug. 1993, EPRI TR-102621.
[3] V. D. Albertson, J. G. Kappenman, N. Mohan, and G. A. Skarbakka, "Load-flow studies in the presence of geomagnetically induced currents," *IEEE Trans. Power App. Syst.*, vol. PAS-100, no. 2, pp. 594–607, Feb. 1981.
[4] L. Bolduc, "GIC observations and studies in the Hydro-Québec power system," *J. Atmospher. Solar-Terrestrial Phys.*, vol. 64, no. 16, pp. 1793–1802, 2002.
[5] Elect. Power Res. Inst., "Solar magnetic disturbances/geomagnetically induced current and protective relaying," EPRI TR-102621, Aug. 1993.
[6] T. S. Molinski, "Why utilities respect geomagnetically induced currents," *J. Atmosph. Solar-Terrestrial Phys.*, vol. 64, no. 16, pp. 1765–1778, 2002.
[7] J. G. Kappenman, , L. L. Grigsby, Ed., "Geomagnetic disturbances and impacts upon power system operation," in *Electrical Power Engineering Handbook*, 2nd ed. Boca Raton, FL: CRC/IEEE, 2007, ch. 16, pp. 16-1–16-22.
[8] IEEE Distribution Planning Working Group, "Radial distribution test feeders," *IEEE Trans. Power Syst.*, vol. 6, no. 3, pp. 975–985, Aug. 1991.
[9] D. H. Boteler, Q. Bui-Van, and J. Lemay, "Directional sensitivity to geomagnetically induced currents of the Hydro-Quebec 735 kv power system," *IEEE Trans. Power Del.*, vol. 9, no. 4, pp. 1963–1971, Oct. 1994.
[10] R. H. Rapp, Geometric Geodesy Part 1, Dept. Geodetic Sci. Surveying, Ohio State Univ., , Columbus, course notes, 1994. [Online]. Available: http://hdl.handle.net/1811/24333

Randy Horton (S'94–M'96–SM'07) received the B.Sc. degree in electrical engineering from the University of Alabama at Birmingham (UAB) in 1996, the M.Sc. degree in electrical engineering from Auburn University, Auburn, AL, in 2002, and the Ph.D. degree in electrical engineering from the University of Alabama, Tuscaloosa, in 2009.

Currently, he is a Senior Project Manager in the Power System Studies Group, Electric Power Research Institute (EPRI). His research activities focus on power quality, time-domain modeling of power systems, system protection, and impacts of geomagnetic disturbances on power systems. He joined EPRI in 2010. Prior to joining EPRI, he was with Southern Company for approximately 14 years where he performed various time-domain (transient), power quality, and system protection and coordination studies with the Southern Company System.

Dr. Horton is an active participant in several working groups in the areas of transmission and distribution and power system relaying. Currently, he is Chair of the IEEE Working Group on Field Measured Overvoltages and Their Analysis, and is a member of Eta Kappa Nu. He is a registered Professional Engineer in the State of Alabama.

David Boteler (SM'92) was born in London, U.K. He received the B.Sc. degree in electronic engineering from the University of Wales, Cardiff, U.K., the M.Sc. degree in geophysics from the University of British Columbia, Vancouver, BC, Canada, and the Ph.D. degree in physics from Victoria University of Wellington, Wellington, New Zealand.

He has more than 30 years of experience working on interdisciplinary problems including work in the Antarctic and Arctic. Since 1990, he has been a Research Scientist with Natural Resources Canada, specializing in space weather and geomagnetic effects on technological systems.

Dr. Boteler is registered as a Chartered Engineer in the U.K. and is Director of the International Space Environment Service.

Thomas J. Overbye (S'87–M'92–SM'96–F'05) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Wisconsin, Madison.

He was with Madison Gas and Electric Company, Madison, from 1983 to 1991. Currently, he is the Fox Family Professor of Electrical and Computer Engineering at the University of Illinois, Urbana-Champaign. His current research interests include power system visualization, power system dynamics, power system cybersecurity, and computer applications in power systems.

Risto Pirjola was born in Helsinki, Finland, in 1950. He received the M.Sc. degree in mathematics and the Ph.D. degree in theoretical physics from the University of Helsinki, Espoo, Finland., in 1971 and 1982, respectively.

Since 1978, he has been a Scientist and Research Manager with the Finnish Meteorological Institute (FMI), including long-term scientific visits to Natural Resources Canada, Ottawa, ON, Canada. He has been a Guest Professor with the North China Electric Power University, Beijing, China, since 2008. His scientific research interests mainly refer to the modeling of the geoelectromagnetic variation field at auroral latitudes, and to studies of geomagnetically induced currents. From 1992 to 1997, he was the Project Manager of FMI's contributions to international planetary exploration projects. He is an author or coauthor of about 100 peer-reviewed papers and 125 other publications.

Roger C. Dugan (M'74–SM'81–F'00) received the B.Sc. degree in electrical engineering from Ohio University, Athens, in 1972 and the M.Eng. degree in electric power engineering from Rensselaer Polytechnic Institute, Troy, NY, in 1973.

Currently, he is Senior Technical Executive for the Electric Power Research Institute, Knoxville, TN. From 1992 to 2004, he was Senior Consultant with Electrotek Concepts, Knoxville. From 1973 to 1992, he held various positions in the Systems Engineering Department, Cooper Power Systems, Canonsburg, PA and Franksville, WI. He has worked on many diverse aspects of power engineering because of his interests in applying computer methods to power system simulation. The focus of his career has been on utility distribution systems. He is coauthor of *Electrical Power Systems Quality* (McGraw-Hill).

Mr. Dugan is the 2005 recipient of the IEEE Excellence in Distribution Engineering Award and Chair of the Test Feeder Working Group of the Distribution System Analysis Subcommittee of the PSACE committee. He was elected an IEEE Fellow in 2000 for his contributions to harmonics and transients analysis.