Effects of the Changes in IEEE Std. 80 on the Design and Analysis of Power System Grounding

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Abstract --**This paper discusses the major changes in the 2000 version of *IEEE Guide for Safety in AC Substation Grounding* (Standard 80-2000) with respect to the 1986 version (Standard 80-1986), which affect the grounding design and analysis. Comparisons are made for the portions in the two versions of the guide where major changes occur. Examples have been presented to show the effects of the changes on the design and analysis of power system grounding.**

Index Terms -- **grounding, safety, touch voltage, step voltage, foot resistance, ground potential rise, decrement factor, derating factor**.

I. INTRODUCTION

IEEE Standard 80, *IEEE Guide for Safety in AC Substation Grounding*, was developed to provide guidance and information pertinent to safe grounding practices in AC substation design. Three editions of IEEE Standard 80 (1961, 1976, and 1986) had been published before the 2000 edition. The newly revised IEEE Standard 80-2000 [1] has been approved for some time and has been used by engineers and professionals in grounding design and analysis. There are changes in Standard 80-2000 with respect to Standard 80-1986 [2], which affect grounding design and analysis. The objective of this paper is to discuss the major changes in the 2000 version with respect to the 1986 version that most affect grounding design and analysis. Pertinent examples are presented.

II. THE TOUCH AND STEP VOLTAGE CRITERIA

The touch and step voltage criteria are derived from the permissible body current, which is the premise of the Standard. There is no direct change in the expressions of the permissible touch and step voltages. The permissible step and touch voltages, in volts, for a 50 kg person are, respectively,

$$V_{step50} = (1000 + 6C_s \cdot \rho_s)\frac{0.116}{\sqrt{t_s}} \tag{1}$$

$$V_{touch50} = (1000 + 1.5C_s \cdot \rho_s)\frac{0.116}{\sqrt{t_s}} \tag{2}$$

where C_s is the surface layer derating factor, which will be discussed in detail later, ρ_s the surface material resistivity in Ω-m, and t_s the duration of the shock current in seconds. The 1000 appearing in (1) and (2) is the human body resistance in Ω.

Even though there is no direct change in the expressions of the permissible touch and step voltages, there are changes in the calculation of the C_s factor and in the application of the decrement factor for the DC current offset, which affect the permissible touch and step voltages. These changes will be discussed in the following sections.

III. THE DERATING FACTOR C_S

One of the most notable changes which affect the grounding design and analysis is the change in the calculation of the C_s factor, which is the surface layer derating factor. The C_s factor is introduced in the computation of foot resistances to account for the effect of a surface layer in a substation (usually a high resistivity crushed rock layer). There are many publications on the calculation of foot resistance and the C_s factor [3-5]. In Standard 80-2000, more accurate formulae have been used for computing the C_s factor, resulting in generally higher values of C_s compared with those in Standard 80-1986. The computation of C_s in Standard 80-1986 is based on a simplified expression, while in Standard 80-2000, it is based on a rigorous series expression, with each term being a surface integral.

For a uniform soil, the foot resistance, R_f, is computed as follows, assuming a conducting plate on the earth surface:

$$R_f = \frac{\rho}{4b} \tag{3}$$

where ρ is the soil resistivity in Ω-m and b the radius of the plate, in meters, which is usually assumed to be 0.08 m. When a surface layer with resistivity ρ_s exists, the foot resistance is expressed as

$$R_f = \left(\frac{\rho_s}{4b}\right)C_s \tag{4}$$

where C_s is the surface layer derating factor, which is a function of the surface layer thickness and the reflection coefficient between the surface layer resistivity and the native soil resistivity, defined as $K=(\rho-\rho_s)/(\rho+\rho_s)$.

In Standard 80-1986, the expression for C_s is

$$C_s = \frac{1}{0.96}\left[1+2\sum_{n=1}^{\infty}\frac{K^n}{\left(1+(2nh_s/b)^2\right)^{1/2}}\right] \qquad (5)$$

where h_s is the surface layer thickness.

In Standard 80-2000, the expression for C_s is

$$C_s = 1+\frac{8}{\pi b^2}\sum_{n=1}^{\infty}K^n\int_0^b r\cdot\sin^{-1}\left(\frac{2b}{R_1+R_2}\right)dr \qquad (6)$$

where R_1 and R_2 are give by

$$R_1 = \left((r+b)^2-(2nh_s)^2\right)^{1/2} \qquad (7)$$

$$R_2 = \left((r+b)^2+(2nh_s)^2\right)^{1/2} \qquad (8)$$

Fig. 1 compares the C_s curves based on the formulae from both versions of the Standard, for $K=-0.1$, $K=-0.5$, and $K=-0.9$.
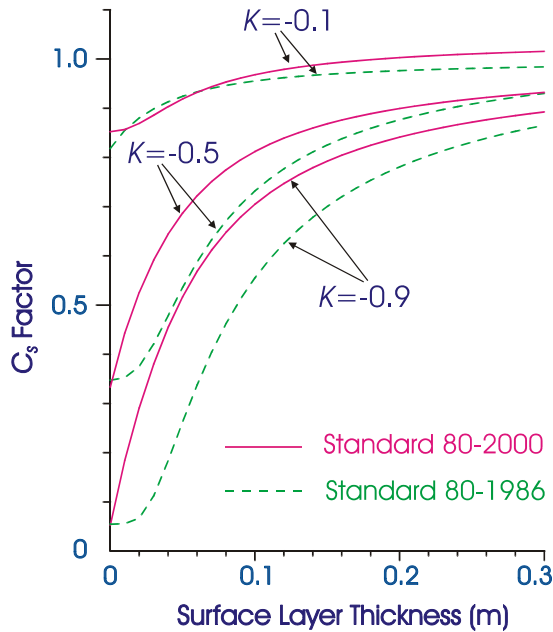

Fig. 1. Cs curves based on Standard 80-1986 and Standard 80-2000.

It can be seen that the C_s factor based on Standard 80-2000 is generally higher than that based on Standard 80-1986. The difference is larger when the reflection coefficient is closer to –1. The implication of higher C_s values is that the corresponding foot resistances based on Standard 80-2000 are higher. As a consequence, the tolerable touch and step voltages are higher, as can be seen from (1) and (2). For example, for a surface crushed rock layer with a resistivity of 2000 Ω-m and a

thickness of 10 cm on top of a native soil with a soil resistivity of 100 Ω-m, $K=-0.9$, $C_{S1986}=0.555$ and $C_{S2000}=0.705$, giving a 27% increase. Using Equations (1) and (2), we can see that the increase in the C_s factor results in a 20% increase in tolerable touch voltage and 25% increase in tolerable step voltage, assuming a body resistance of 1000 Ω.

The lower tolerable touch and step voltages based on Standard 80-1986 mean that the design of a grounding system is a conservative one, possibly an overdesign. The higher tolerable touch and step voltages based on Standard 80-2000 make the design of grounding system easier. Note that the differences in the tolerable touch and step voltages based on the two versions of the Standard generally increase as the magnitude of the reflection coefficient increases and the surface layer thickness decreases, as evidenced by Fig. 1.

IV. THE DECREMENT FACTOR D_f

Because the design of a grounding system must consider the asymmetrical current, a decrement factor is introduced to take into account the effect of DC current offset during a fault. Careful readers may have noticed that the expressions for the decrement factor in the two versions of the Standard are different. However, there is no intended change in the expression of the decrement factor D_f. The difference arises from a typographical error in the 1986 version. The 2000 version has simply corrected this. In the application of the decrement factor, however, the two versions have slightly different interpretations. A table showing typical values of the decrement factor in the 2000 version includes time durations of the fault up to 1 s, while the 1986 version recommends a value of 1.0 for D_f for fault durations of 0.5 s or more and considers such a value to be conservative. The 2000 version states that a value of 1.0 for D_f for fault duration of 0.5 s or more can be used, without further comment. It is obvious that if the computed value for D_f is used for longer fault durations, then the grounding design will always be conservative. For example, for a fault duration of 0.5 s and a typical X/R ratio (ratio of the system reactance to resistance) of 20, the calculated value of D_f is 1.052. If $D_f=1.052$ is used in the safety calculation of a grounding design, quantities such as grid GPR (Ground Potential Rise), touch voltage, and step voltage will be 5.2% larger compared to the use of $D_f=1.0$.

V. THE UNIFORM SOIL ASSUMPTION

There are major changes in the chapters dealing with soil structure and selection of a soil model (Chapter 13 in Standard 80-2000 and Chapter 11 in Standard 80-1986). These changes include a new table showing typical surface material resistivities, a description of the uniform soil assumption procedure, addition of a two-layer model and an associated graphical method, and the introduction of a brief discussion of multilayer soils. All the changes provide useful information except for

the change dealing with the uniform soil assumption, which may lead to incorrect grounding designs if not applied carefully. The misleading effect is further enhanced by the introduction of the erroneous Annex E, entitled "Equivalent Uniform Soil Model for Nonuniform Soils."

Two formulae are presented for the calculation of the resistivity of a uniform soil model, based on measured resistivity, in Chapter 13 of Standard 80-2000,

$$\rho_{av1} = \frac{\rho_{a(1)} + \rho_{a(2)} + \rho_{a(3)} + \cdots + \rho_{a(n)}}{n} \qquad (9)$$

$$\rho_{av2} = \frac{\rho_{a(min)} + \rho_{a(max)}}{2} \qquad (10)$$

where $\rho_{a(1)}, \rho_{a(2)}, \rho_{a(3)}, \cdots, \rho_{a(n)}$ are the measured apparent resistivity data at different spacings using the four-pin method, n the number of measurements, and $\rho_{a(min)}$ and $\rho_{a(max)}$ the minimum and maximum values of the measured apparent soil resistivity.

The flaws in the uniform soil assumption using (9) and (10) are as follows:

(a) Uniform soils seldom exist in practice.

(b) Both formulae only relate the average soil resistivity to the measured apparent resistivities, not to the electrode spacings at which they were measured. It is well known that the shallow soil resistivities exert greater influence on smaller grounding grids and deep soil resistivities have a greater effect on larger grounding grids. Measurements made at short electrode spacings reflect surface soil resistivities and measurements made at large electrode spacings reflect deeper soil resistivities.

(c) Depending on the distribution of electrode spacings chosen, the average soil resistivity using (9) will vary significantly. For example, if more measurement points are taken for short spacings and fewer measurement points for large spacings, then the top soil resistivity will have more weight in the calculation of the average resistivity using (9). See [6] for details on how limited electrode spacings can introduce error into grounding analysis predictions.

Let us consider two two-layer soil types as shown in Table I.

TABLE I
TWO-LAYER SOIL TYPES

Soil Type 1		Soil Type 2	
Soil Resistivity	Layer Thickness	Soil Resistivity	Layer Thickness
100 Ω-m	6.1 m	300 Ω-m	6.1 m
300 Ω-m	∞	100 Ω-m	∞

Computer simulated soil resistivity measurements in the above two soil types are made and the results are shown in Table II. If (10) is used to compute the average resistivity, then the two average resistivities corresponding to the two soil types are ρ_1=195.3 Ω-m and ρ_2=199.7 Ω-m, respectively. Actually, if the measurement spacing is large enough, we will always have $\rho_1 = \rho_2 \approx 200$ Ω-m. Let us now consider a 64-mesh 5m × 5m grounding grid and a 64-mesh 200m × 200m grounding grid, buried at a depth of 0.5 m, in Soil Type 1 and Soil Type 2. The ground resistances computed with the two-layer soils and with the average soil resistivity of 200 Ω-m are shown in Table III.

TABLE II
COMPUTER SIMULATED SOIL RESISTIVITY
MEASUREMENTS IN SOIL TYPES 1 AND 2

Electrode Separation		Soil Type 1	Soil Type 2
(ft)	(m)	Apparent Resistivity (Ω-m)	Apparent Resistivity (Ω-m)
1	0.305	99.7	299.0
3	0.915	100.1	299.5
5	1.524	100.6	298.4
15	4.573	111.3	271.6
20	6.098	121.0	248.7
30	9.146	143.1	202.6
50	15.24	181.7	144.2
70	21.34	208.8	120.3
90	27.44	227.2	110.7
110	33.54	241.5	106.4
130	39.63	251.8	104.2
150	45.73	259.6	103.1
200	60.96	272.7	101.7
400	121.92	290.9	100.4

TABLE III
GROUND RESISTANCES COMPUTED WITH
TWO-LAYER SOILS, COMPARED WITH
THOSE COMPUTED WITH AVERAGE UNIFORM SOIL

Grid Dimension	Soil Type 1	Soil Type 2	Uniform (200 Ω-m)
5m × 5m	9.22 Ω	19.4 Ω	15.0 Ω
200m × 200m	0.58 Ω	0.33 Ω	0.48 Ω

It can be seen from Table III that in Soil Type 2 the ground resistance of the small grid is larger than that in Soil Type 1 while for the large grid the reverse is true. These results show that for the small grid the top layer resistivity has a larger influence and for the large grid the bottom layer has a larger influence. Use of the average soil resistivity results in an error of 63% for the small grid in Soil Type 1 and 23% in Soil Type 2. In fact, to obtain the same ground resistance of the small

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grid in Soil Type 1, the average soil resistivity should be 123 Ω-m instead of 200 Ω-m as proposed by the use of (10). Similarly, to obtain the same ground resistance of the large grid in Soil Type 2, the average soil resistivity should be 138 Ω-m instead of 200 Ω-m.

The newly added Annex E in Standard 80-2000 gives an example of equivalent uniform soil for nonuniform soils. In the above example, the two soil types are the same as those in Annex E of Standard 80-2000, for comparison purposes. It should be pointed out that Tables E.1 and E.2 in Annex E of Standard 80-2000 contain erroneous values. Table E.2 in Annex E shows the mathematically derived apparent resistivities for the two soil types. The first three values of the resistivities have significant errors. For example, for Soil Type 1 in Table E.2 of Annex E, the first derived soil resistivity value corresponding to a probe spacing of 0.305 m is 56.94 Ω-m. Anyone with experience in soil resistivity measurement and interpretation will immediately realize that this value theoretically cannot be lower than 100 Ω-m, unless overly long electrodes are used for the measurements and no correction is made to account for the coupling between them. This appears to be the case in Annex E: the wrong data is therefore used in the calculation of the average soil resistivity in Annex E. Consequently, the results shown in Table E.1 of Annex E cannot be referenced with any confidence. In reality, if the electrode spacings include a very short spacing and a very large spacing, the calculated average resistivity should be 200 Ω-m for both soil types. This is why we have used 200 Ω-m in our example. Obtaining a good equivalent uniform soil to represent a multilayer soil is never an easy task, if ever possible. As described in [7], in some cases, different equivalent uniform or two-layer soils can be used to establish lower and upper bounds for ground parameters in a multilayer soil. Interested readers may refer to [7] for a detailed analysis of the equivalence of uniform and two-layer soils to multilayer soils.

VI. MULTILAYER SOIL MODEL

A subsection regarding multilayer soil models, which is not in Standard 80-1986, is added in Standard 80-2000. It briefly describes the method of multilayer analysis and presents some references. In practice, most soil structures are multilayered and require appropriate computer modeling for accurate results. Interested readers may refer to [8-10] for grounding analysis in multilayer soils.

VII. GRID CURRENT COMPUTATION

It is known that for a typical grounding analysis, the basic information required concerns the following: grounding system configuration and characteristics, soil structure, and fault current. Generally, the information provided regarding the fault current is the fault current flowing into the faulted substation from the faulted phase conductors. This information, however, cannot be used directly in a grounding analysis in most cases, without undue conservatism. Instead, it is used to derive

the grid current, i.e., the current discharged into the earth by the grounding grid of the faulted substation. In Standard 80-2000, a new annex, Annex C, has been added to analyze the current division using a graphical, approximate method. Examples have also been provided to illustrate the use of the graphical analysis. The information provided in Annex C is useful. However, it is preferable to use computer programs to compute fault current distribution because accurate results can easily be obtained. While using the graphical method, the system under consideration has to be reasonably similar to those covered by the graphics. Principles of such programs are described in [11-12]. Typical computation results can be found in [13]. Following is an example showing the computation of grid current.
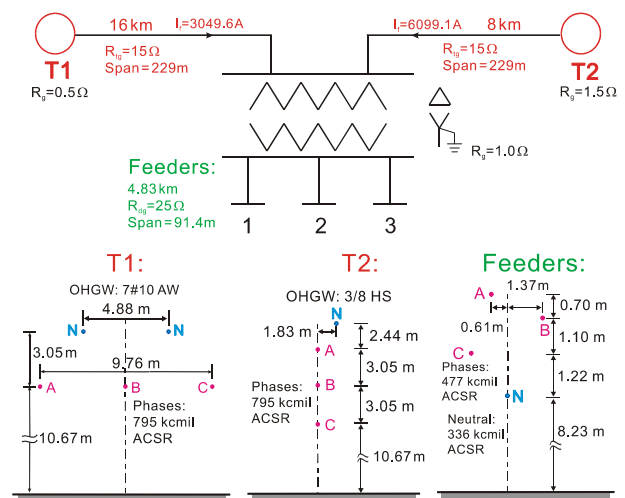

Fig. 2. System and configuration data for fault current distribution computation.
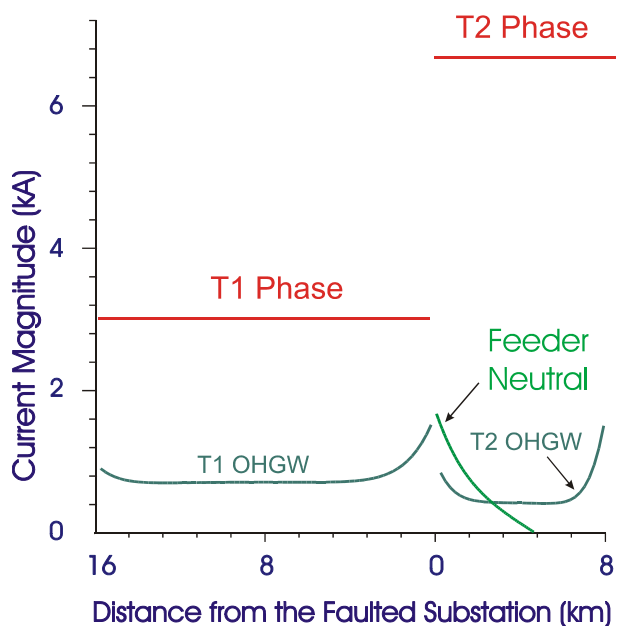

Fig. 3. Fault current in the phase and neutral conductors.

Fig. 2 shows the system and configuration data. Fig. 3 shows the computed current distribution in the phase

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and overhead ground (OHGW) conductors of the transmission line and in one of the three distribution feeder neutrals. It can be seen that there is a significant amount of the fault current returning to the sources through the OHGW of the transmission line. Furthermore, there is a significant amount of the fault current flowing in the distribution feeder neutrals. Obviously, the existence of the distribution feeder neutrals will help lower the fault current discharged by the grounding grid at the faulted substation. In this example, the fault current discharged by the grounding grid is 2422 A, representing 27% of the total fault current. Using the graphical method presented in Annex C of Standard 80-2000, the grid current is 2726 A, 13% more than in reality. The discrepancy and resulting overdesign is considerably greater when optical fibre overhead ground wires are involved.

VIII. GROUNDING OF SUBSTATION FENCE

Newly extended Section 17.3 in Standard 80-2000 deals with grounding of substation fences in much greater detail than in Standard 80-1986. The following cases have been discussed: (1) fence within the grounding area; (2) fence on grid perimeter; (3) fence outside the grounding area but close by; (4) fence outside the grounding area and far away. One case which is absent, but is of significance, is when part of the fence is close to the grounding grid and part of it far away. The information provided in Section 17.3 is therefore useful, but not complete. Interested readers may refer to [14] for a detailed safety analysis of fence interconnections to substation grounding systems. The following example is intended to demonstrate appropriate fence grounding for the case when part of the fence is close to the grounding grid and part far away.

Fig. 4 shows a grounding grid at the left side of a large fenced area whose dimensions are 350m × 100m. The isolation of the fence between the left and right sides is made by creating 3 m gaps at the junction points. Each 3 m gap represents an isolated fence section. The left side of the fence is always connected to the grounding grid.
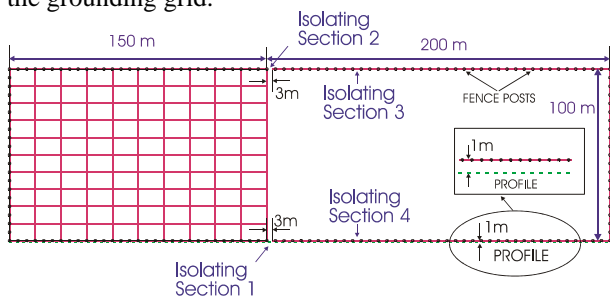

Fig. 4. Grounding grid in a large fenced area.

Fig. 5 shows the touch voltages with respect to the fence for three cases: (1) no isolating section; (2) with isolating sections 1 and 2, as shown in Fig. 4; (3) with all the four isolating sections shown in Fig. 4. Note that the portion of the fence left of isolating sections 1 and 2 is always connected to the grid while the portions of the

fence to the right of isolating sections 1 and 2 always remain disconnected from the grid when isolating sections are installed.

We can see from Fig. 5 that without any isolating section, the touch voltages are very high in the proximity of the fence away from the grid. The reason is that high potentials are transferred to this portion of the fence, while fence posts alone are not adequate to raise the earth potentials significantly along the fence and thereby reduce touch voltages at these locations. When isolating sections 1 and 2 are installed, the touch voltages at these locations decrease considerably, except at locations close to the isolating sections. To reduce the high touch voltages at locations close to isolating sections 1 and 2, isolating sections 3 and 4 are installed. As shown in Fig. 5, the touch voltages at these locations are much lower now and at other locations also remain low. By using four isolating sections we have reduced the touch voltage everywhere to below 800 V. The permissible touch voltage in this case is 856 V for a fault clearing time of 0.35 s, a surface crushed stone layer with a thickness of 15 cm and a resistivity of 3000 Ω-m, and a native soil resistivity of 100 Ω-m.
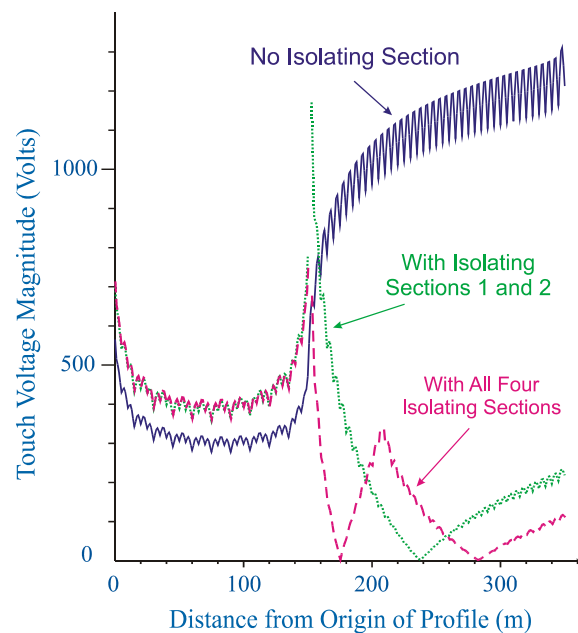

Fig. 5. Touch voltages along fence.

It should be pointed out that the permissible touch voltage, 856 V, is calculated based on Standard 80-2000. It would be 751 V if it were calculated based on Standard 80-1986. In this case the grid has to be enhanced at the location close to isolating sections 1 and 2 in order to lower the touch voltages at the locations that exceed 751 V. We see from this example that the changes in Standard 80 do affect grounding design.

IX. CONCLUSIONS

The major changes in the 2000 version of IEEE Guide for Safety in AC Substation Grounding (Standard 80-2000) with respect to the 1986 version (Standard 80-1986), which affect the grounding design and analysis,

have been discussed. Comparisons are made for the portions in the two versions of the Standard where changes occur. Examples have been presented to show the effects of the changes in the grounding design and analysis.

X. ACKNOWLEDGMENTS

XI. REFERENCES

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XII. BIOGRAPHIES

Dr. Jinxi Ma (M'91, SM'00) was born in Shandong, P. R. China in December 1956. He received the B.Sc. degree from Shandong University, P. R. China, and the M.Sc. degree from Beijing University of Aeronautics and Astronautics, both in electrical engineering, in 1982 and 1984, respectively. He received the Ph.D. degree in electrical and computer engineering from the University of Manitoba, Winnipeg, Canada in 1991.

From 1984 to 1986, he was a faculty member with the Department of Electrical Engineering, Beijing University of Aeronautics and Astronautics. He worked on projects involving design and analysis of reflector antennas and calculations of radar cross sections of aircraft. Since September 1990, he has been with the R & D Dept. of Safe Engineering Services & technologies in Montreal, where he is presently serving as manager of the Analytical R & D Department. His research interests are in transient electromagnetic scattering, EMI and EMC, and analysis of grounding systems in various soil structures.

Dr. Ma is the author of more than eighty papers on transient electromagnetic scattering, analysis and design of reflector antennas, power system grounding, lightning, and electromagnetic interference. He is a senior member of the IEEE Power Engineering Society, a member of the IEEE Standards Association, and a corresponding member of the IEEE Substations Committee and is active on Working Groups D7 and D9.

Dr. Farid P. Dawalibi (M'72, SM'82) was born in Lebanon in November 1947. He received a Bachelor of Engineering degree from St. Joseph's University, affiliated with the University of Lyon, and the M.Sc. and Ph.D. degrees from Ecole Polytechnique of the University of Montreal.

From 1971 to 1976, he worked as a consulting engineer with the Shawinigan Engineering Company, in Montreal. He worked on numerous projects involving power system analysis and design, railway electrification studies and specialized computer software code development. In 1976, he joined Montel-Sprecher & Schuh, a manufacturer of high voltage equipment in Montreal, as Manager of Technical Services and was involved in power system design, equipment selection and testing for systems ranging from a few to several hundred kV. In 1979, he founded Safe Engineering Services & technologies, a company specializing in soil effects on power networks. Since then he has been responsible for the engineering activities of the company including the development of computer software related to power system applications.

He is the author of more than one hundred and fifty papers on power system grounding, lightning, inductive interference and electromagnetic field analysis. He has written several research reports for CEA and EPRI.

Dr. Dawalibi is a corresponding member of various IEEE Committee Working Groups, and a senior member of the IEEE Power Engineering Society and the Canadian Society for Electrical Engineering. He is a registered Engineer in the Province of Quebec.

For the biography of **Mr. Robert D. Southey**, please see "Improving the reliability of power systems with more accurate grounding system resistance estimates" in the proceedings of IEEE-PES/CSEE International Conference on Power System Technology, Kunming, China, Oct. 13-17, 2002.