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United States Department of the Interior

GEOLOGICAL SURVEY
Box 25046
Denver Federal Center
Denver, Colorado 80225

IN REPLY REFER TO: Stop 964

15 April 77

Dear Electrical Properties User,

It has been very apparent for a long time that there should be some standardization of the nomenclature and parameters of electrical properties, both in general terms and specifically as applied to IP, complex resistivity, and so forth.

We have formed a small committee in the U.S.G.S. to initiate this effort of standardization. This letter is going to as many people as we know of with interests in the area of electrical properties in order to solicit comments and suggestions.

We would like to act as a clearing center to receive the comments and opinions of all interested parties as to their desired nomenclature and parameters for electrical properties. If you will write us a detailed letter, describing what you would like to see for a standard, we will collect and summarize this into one review document. This document will then be sent along with a summary recommendation (compiled by us) as a first draft of the proposed standards for electrical properties nomenclature and parameters. You will then be given an opportunity to respond with further comments, which we will adopt into a final draft.

If little controversy arises on the revised draft, the U.S.G.S. will adopt it as a standard, and we will submit it to the SEG through the Mining Committee for their consideration as a standard. If a consensus is not readily reached on standards, the U.S.G.S. will undertake to sponsor a short meeting for the purpose of attaining a consensus.

Any interested party may participate, so please circulate or post this letter.

Sincerely,

Gary R. Olhoeft
James Scott
Bruce Smith
Jeff Wynn

reply by 1 July 77 to:
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AMERICAN REVOLUTION BICENTENNIAL 1776-1976

DRAFT

ELECTRICAL PROPERTIES STANDARD NOMENCLATURE

The geophysical community has a wide variety of terms and parameters in use today for the description of electrical properties results. Most of the definitions of terms are not very carefully defined and very few are derived from fundamental physics relating back to such principles as Maxwell's Equations. Such available standards as the ASTM-D-150-70 definitions for dielectrics and ASTM-D-257-66 for resistances are incomplete and do not cover such topics as complex resistivity, chargeability, and so on.

Without an adequately defined set of standard nomenclature, it is a nearly hopeless task to attempt to relate field surveys of electrical methods taken with one instrument to those of a different instrument, and it is a worse task yet in trying to relate field results to laboratory measurements. In some cases, it has not even been possible to relate measurements between different laboratories.

Basically any parameterization of data which may be related back to fundamental physical principles and laws would be an acceptable way of presenting data, but there are then too many possibilities. It would also be too time consuming to continually rederive and prove the relation to physics. Thus, this draft standard is an attempt to derive a series of parameters to be used in the description of electrical properties in the primary literature.

This draft will start with Maxwell's Equations via the propagation constant and derive the fundamental forms of electrical properties parameters. Then useful geophysical terms will be derived, and finally a standard set of terms will be defined and recommended as the only method of presenting data in the primary literature. NOTE: this description is for linear systems only. Nonlinear electrical properties will be treated later when they have been investigated further.

From Maxwell's Equations (Stratton, 1941; Ward, 1967; and others) all of the electromagnetic physical properties information about a material is contained within the propagation constant, k :

$$k^2 = -j \mu \omega S \quad (1)$$

where $j = \sqrt{-1}$

$\omega = 2 \pi f$ (where f is frequency in Hertz)

and the magnetic properties are completely characterized in μ, while the electrical properties are completely characterized in S.

The magnetic permeability, μ (Henry/meter), may be complex (frequency dependent), non-linear (field dependent), anisotropic, tensor, and variable with position in the material. In general

$$B = G(H)$$

and is usually assumed to be

$$B = \mu H$$

where B = magnetic induction (Weber/m^2)

H = magnetic field (ampere-turn/m)

G ="function of...".

These terms are adequately discussed and defined in Nagata (1961), Miles et alia (1957), and Olhoeft and Strangway (1974).

The electrical admittivity or total electrical conductivity, S (Siemens/m), may also be complex, non-linear, and so on as for the magnetic permeability. In a simple material with no net charge distribution and which is homogeneous, isotropic, and linear the electrical constituitive relation is

$$\omega D - j J = -j S E \quad (2)$$

where D = electrical displacement (coulomb/m^2)

J = current density (ampere/m^2)

E = electric field (volt/m).

This is more generally written in the parameteric form as

$$D = G(E)$$

$$J = G'(E)$$

which are normally assumed to be

$$D = \varepsilon E$$

$$J = \sigma E$$

where ε = dielectric permittivity (farad/m)

σ = electrical conductivity (Siemens/m).

Thus in equation (2) above

$$S = \sigma + j \omega \varepsilon. \qquad (3)$$

Due to several causes (see below), the electrical admittivity is frequency dependent and thus complex of the form (Fuller and Ward, 1970)

$$S' + j S'' = \sigma' + j \sigma'' + j \omega (\varepsilon' - j \varepsilon'') \qquad (4)$$

where σ', σ'', ε', and ε'' are all frequency dependent.

Thus, the following terms are defined:

$S' + j S''$ = complex electrical admittivity (complex total electrical conductivity)

$\sigma' + j \sigma''$ = complex ohmic/diffusion electrical conductivity

$\varepsilon' - j \varepsilon''$ = complex dielectric permittivity

$(\varepsilon' - j \varepsilon'')/ \varepsilon_0 = K' - j K''$ = complex dielectric constant

ε_0 = vacuum permittivity = 8.854185×10^{-12} farad/m

K' = dielectric constant

$D = \cot \theta = S' / S'' = (\sigma' + \omega \varepsilon')/(\sigma'' + \omega \varepsilon'')$ = loss tangent

θ = electrical phase angle

$\rho' - j \rho'' = (S' + j S'')^{-1}$ = complex electrical resistivity

$\sigma_{DC} = \rho_{DC}^{-1} = \lim_{\omega \to 0} S$ = DC electrical conductivity.

RECOMMENDED PARAMETERS

FORMAT: name : symbol : units

1.0 DIELECTRIC CONSTANT : K' : dimensionless

The dielectric constant is the real part of the complex dielectric permittivity relative to the permittivity of vacuum. It is the ratio of the capacitance of a given configuration of electrodes with a material separating the electrodes to the capacitance of the same electrode configuration with vacuum in place of the material.

1.1 CAPACITANCE : C : farad

The capacitance is that property of a system of conductors and dielectrics which permits the storage of electrically separated charges when potential differences exist between conductors. It is the ratio of a quantity of charge of electricity, Q, to a potential difference, V. It is given as C = Q/V when V is in volts, Q is in coulombs, and thus C is in farads.

1.2 PERMITTIVITY : ε : farad/meter

The permittivity is the capacitance per unit length measurement of the electrical storage capability of vacuum or material dielectrics. The vacuum or free space permittivity = $\varepsilon_o = 8.854185 \times 10^{-12}$ F/m.

2.0 LOSS TANGENT : D : dimensionless

The loss tangent is the cotangent of the phase angle.

$D = \cot\theta = S' / S'' = (\sigma' + \omega\varepsilon') / (\sigma'' + \omega\varepsilon'') = \rho' / \rho''$

3.0 PHASE ANGLE : θ : radians

The phase angle is the angular phase difference between the sinusoidal alternating potential difference (or electric field) applied to a material and the component of the resulting alternating current (or current density) having the same period as the potential difference (or electric field).

4.0 COMPLEX RESISTIVITY : $\rho' - j\,\rho''$: ohm-meter

The complex resistivity is defined in terms of amplitude and phase or real and imagniary parts by ratios of electric field to current density (or potential difference to current times a geometric factor):

$E(t)$ = electric field = $E_s + E_o \sin(\omega t + \phi_E)$

$J(t)$ = current density = $J_s + J_o \sin(\omega t + \phi_J)$

Thus,

$$|\rho| = (\rho'^2 + \rho''^2)^{1/2} = E_o / J_o = \text{resistivity magnitude}$$

$$\angle\rho = \theta = \phi_E - \phi_J = \text{arccot}(\rho'/\rho'') = \text{arccot } D = \text{phase angle}$$

$$\rho' = (E_o/J_o)\cos\theta = \text{real resistivity}$$

$$\rho'' = (E_o/J_o)\sin\theta = \text{imaginary resistivity.}$$

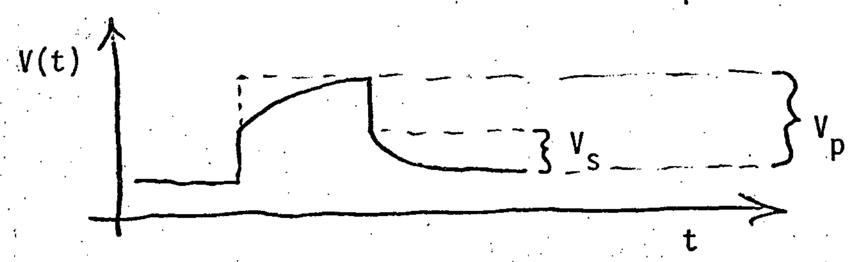
5.0 DECADE PERCENT FREQUENCY EFFECT : DPFE : percent

$$\text{DPFE} = \frac{\rho'(f_2) - \rho'(f_1)}{\rho'(f_1)} \times \frac{100}{\log_{10}(f_1/f_2)} \qquad f_1 > f_2$$

6.0 CHARGEABILITY : m : dimensionless

The chargeability may be defined in several ways.

The chargeability is the ratio of the secondary voltage response to the primary voltage stimulus: $m = V_s / V_p$



It may also be defined (consistantly with above) as:

$$m = \frac{FE}{1 + FE} \qquad \text{where FE = frequency effect} = \frac{\rho'(f_2) - \rho'(f_1)}{\rho'(f_1)}$$

6.0 CHARGEABILITY (Continued)

The m so defined as chargeability is consistant with definitions given in Seigel (1959). An additional (but somewhat model dependent) chargeability that is also consistant with the above is that given by Pelton (1977):

From equation (4) of the preceding discussions,

$(\rho' - j\,\rho")^{-1} = S' + j\,S" = \sigma' + j\,\sigma" + j\,\omega\,(\varepsilon' - j\,\varepsilon")$

and the complex σ is the result of ohmic and faradaic diffusion processes with a general form

$$\sigma' + j\,\sigma" = \sigma_{DC}\,[\,1 + m\,G(n,\,m,\,\omega\tau)]$$

and the chargeability of Pelton (1977) is the m of this equation with the assumed model

$$G = \frac{(\,j\omega\tau\,)^n}{1 + (\,j\omega\tau\,)^n\,(1-m)}$$

where n = diffusion distribution parameter ($\sim$0.5 for pure diffusion)
τ = diffusion relaxation time constant
m = diffusion chargeability (= 0 for pure ohmic conduction).

An alternate and completely parallel model is also possible for the dielectric chargeability due to non-faradaic and dielectric relaxation processes with a general form

$$\varepsilon' - j\,\varepsilon" = K_\infty\,\varepsilon_0\,[\,1 + \xi\,\Gamma(\alpha,\,\omega\tau)]$$

where the model that is usually assumed is the Cole-Cole dielectric distribution (Cole and Cole, 1941; Olhoeft, 1977)

$$\Gamma = [\,1 + (\,j\omega\tau\,)^\alpha\,]^{-1}$$

where α = dielectric distribution parameter (= 1 for single relaxation)
τ = dielectric relaxation time constant
ξ = dielectric chargeability.

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