Essentials of Earthing Design

IEEE 80-2000

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Essentials of IEEE 80-2000 Earthing Design

Abstract

- Emphasize the importance of correctly designed earthing system
- Understand the various factors that drive earthing design
- Provide a general guide to Electrical Engineers how to design an earthing system to comply with IEEE 80-2000
- Understand the metrics of a correctly designed earthing system that complies to IEEE 80-2000

Note:
This presentation does not intend to present the calculation details of earthing design due to time limitation. IIEE-PTDC offers a 16hour detailed course designed to be CPD-accredited, complete with actual design workshop. For those who are interested, please contact:

IIEE-PTDC email: trainingiiee@yahoo.com

The Importance of Correct Earthing Design

- Establish, as design basis, safe limits of potential differences in a substation under fault conditions between points that can be contacted by the human body.

- Review earthing practices with special reference to safety and develop criteria for a safe design.

- Provide a design procedure of practical earthing systems, based on these criteria.

- Develop analytical methods to understand and solution of typical gradient problems

Condition of Danger

Factors that Drive Earthing Design

During typical earth fault conditions, the flow of current to earth will produce potential gradients within and around a substation.

Earthing design must address the circumstances that make electric shock accidents possible, as follows:

- *Relatively high fault current to ground* in relation to the area of ground system and its resistance to remote earth
- *Soil resistivity and distribution of ground currents* such that high potential gradients may occur at points at the earth's surface
- *Presence of an individual at such a point, time, and position* that the body is bridging two points of high potential difference.
- *Absence of sufficient contact resistance or other series resistance to limit current through the body* to a safe value under above circumstances
- *Duration of the fault and body contact,* and hence, of the flow of current through a human body for a sufficient time to cause harm at the given current intensity

Tolerable Body Current Limit

Factors that Drive Earthing Design

The most common physiological effects of electric current on the body, in order of increasing current magnitude are: a) *threshold perception; b) muscular contraction; c) unconsciousness; d) fibrillation of the heart; e) respiratory nerve blockage; f) burning.*

- *1 mA - threshold of perception; current magnitude at which a person is just able to detect a slight tingling sensation caused by the passing current*
- *1–6 mA - "let-go" currents, unpleasant to sustain, but generally do not impair the ability of a person holding an energized object to control his muscles and release it*
- *9–25 mA - painful and difficult or impossible to release energized objects grasped by the hand. Higher currents muscular contractions could make breathing difficult*
- *60–100 mA - ventricular fibrillation, stoppage of the heart, or inhibition of respiration might occur and cause injury or death*

Range of Tolerable Current

Factors that Drive Earthing Design

The current magnitude (I_B) and duration (t_s) that 99.5% of all persons can safely withstand, without ventricular fibrillation is given by the following formula:

$$I_B = 0.116 \div \sqrt{t_s}$$; for 50kg body weight

$$I_B = 0.157 \div \sqrt{t_s}$$; for 70kg body weight

Where:

I_B = Tolerable body current

t_s = Time of exposure to fault current

Accidental Earthed Circuit

Factors that Drive Earthing Design

Human Resistance (IEEE-80) = 1000 ohms

Hand and Foot Contact = 0 ohm

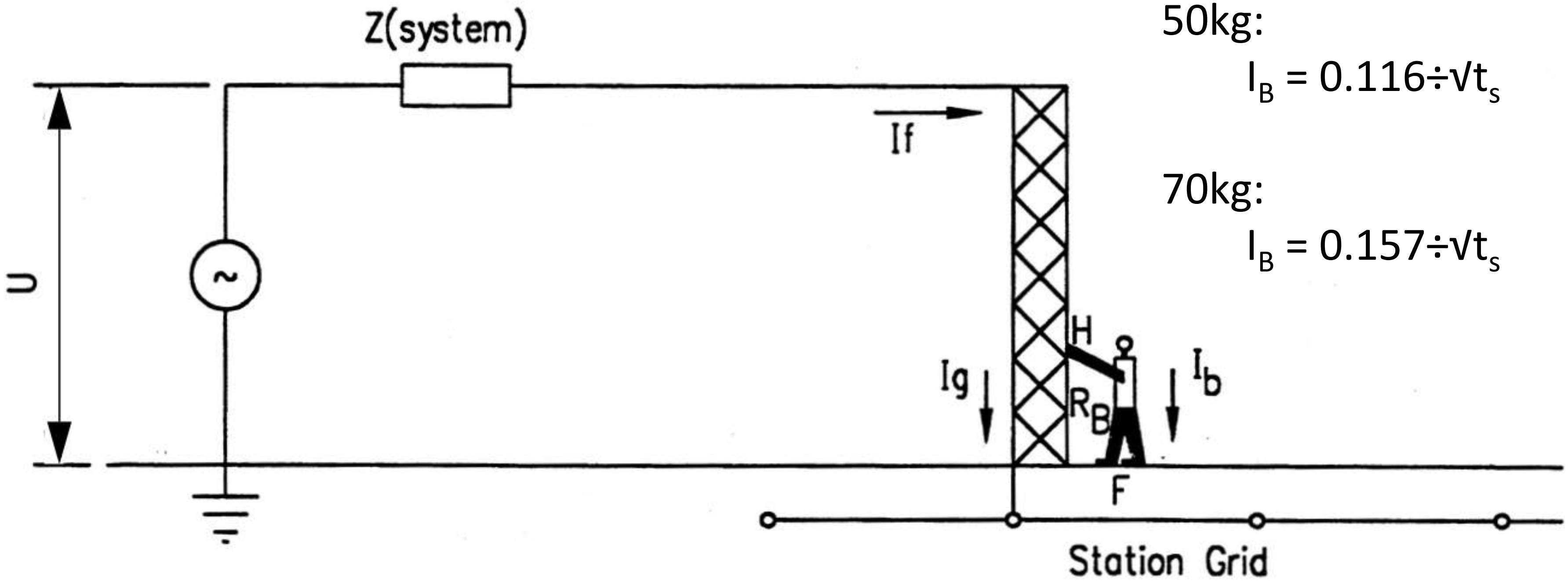
Glove and Shoe Resistance = 0 ohm

Current Paths thru the body are between:

- Hand to one or both feet (touch potential)
- Both feet (step potential)

Tolerable Voltage

Factors that Drive Earthing Design



50kg:

$I_B = 0.116 \div \sqrt{t_s}$

70kg:

$I_B = 0.157 \div \sqrt{t_s}$

- I_b = body current, in A
- R_A = effective body resistance in Ω
- V_A = effective voltage of the accidental circuit (touch or step voltage) in V

Tolerable Voltage

Factors that Drive Earthing Design

The permissible total equivalent voltage is:

- $E_{touch} = I_B x (R_B + 1.5\rho)$

- $E_{step} = I_B x (R_B + 6.0\rho)$

Where:

I_b - body current through the accidental circuit, in A

R_B - total effective resistance of the accidental circuit in Ω

ρ - homogeneous earth resistivity, in Ω-meter

Surface Material Resistivity

Factors that Drive Earthing Design

- A layer of high resistivity material (gravel) is often spread above the earth grid to increase contact resistance between the soil and the feet of persons in the substation
- The current through the body will be lowered considerably with the addition of the surface material because of the greater contact resistance between the earth and the feet
- The reduction depends on the relative values of the soil and the surface material resistivities, and on the thickness of the surface material.

Magnitude of Fault Current

Factors that Drive Earthing Design

Symmetrical Earth Fault Current

- The maximum RMS value of symmetrical fault current after the instant of a earth fault initiation
- Represents the RMS value of the symmetrical component in the first half-cycle of a current wave that develops after the instant of fault at time zero.

For phase-to-ground faults:

$$I_{f(0+)} = 3I''_0$$

Where:

$I_{f(0+)}$ - Initial RMS symmetrical ground fault current

I''_0 - RMS value of zero-sequence symmetrical current that develops immediately after the instant of fault initiation, reflecting the subtransient reactances of rotating machines contributing to the fault

$$\textit{Symmetrical Earth Fault Current} = I_f = 3I_0$$

Duration of Fault Current

Factors that Drive Earthing Design

Tolerable Earth Fault Current is inversely related to the square root of exposure time:

$$I_B \; \alpha \; k \div \sqrt{t_s}$$

** Short exposure time means high tolerable values*
** Long exposure time means low tolerable values*

The allowed current value must be based on ***CLEARING TIME*** of:

- Primary protective devices
- Backup protective devices

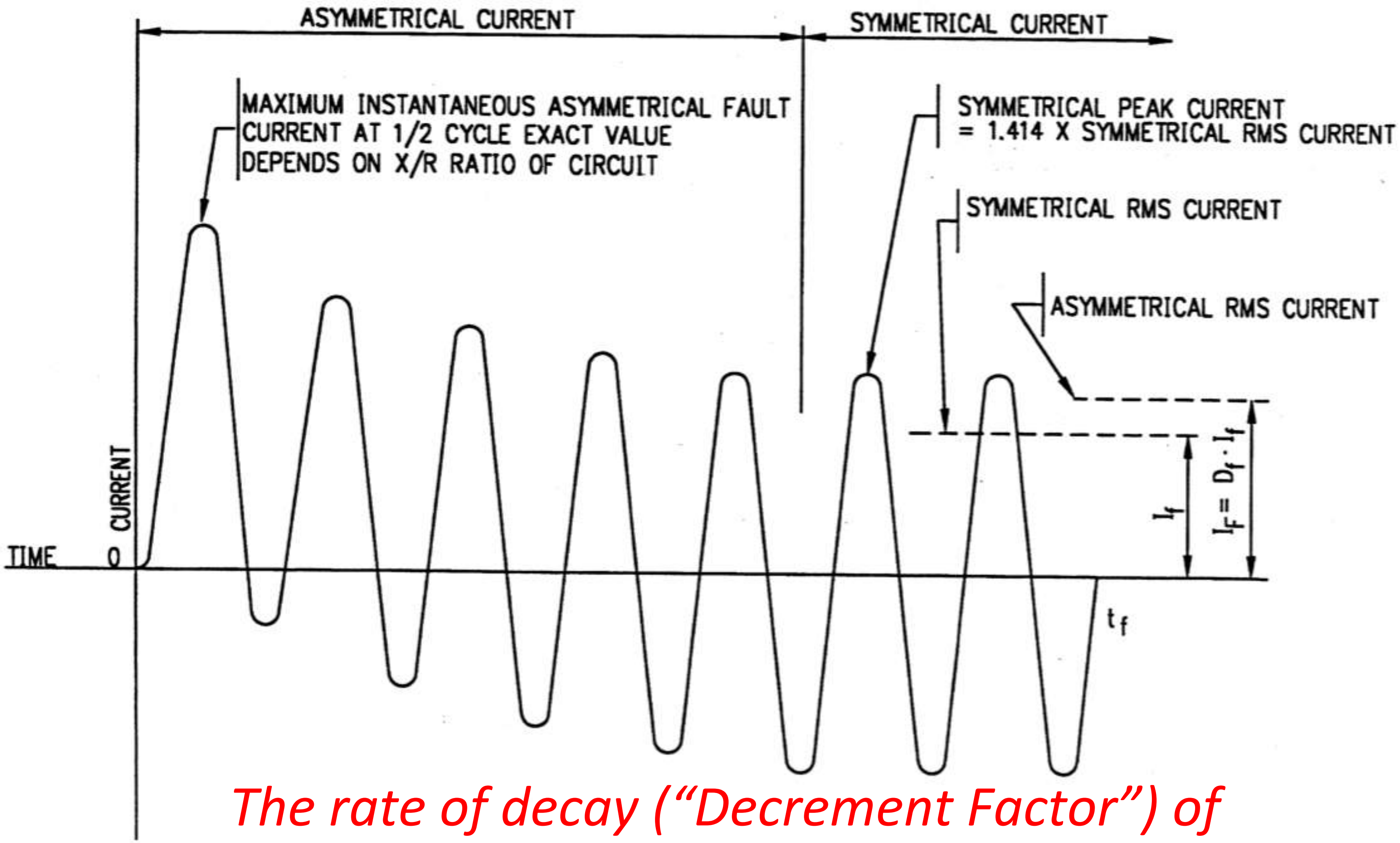
Primary protection clearing time *is possible due to* ***low combined probability*** *that* ***relay malfunctions*** *will coincide with all other adverse factors necessary for an accident*

Backup protection clearing time *is* ***more conservative*** *because of* ***greater safety margin***

Research provides evidence that a human heart becomes increasingly susceptible to ventricular fibrillation when the time of exposure to current is approaching the heartbeat period, but the danger is much smaller if the time of exposure to current is in the region of 0.06s to 0.3s (3.6cycles to 18 cycles)

System X/R Ratio

Factors that Drive Earthing Design



The rate of decay ("Decrement Factor") of asymetrical fault current to symmetrical value is dictated by the system X/R ratio at the point of fault.

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Levels of Design Engineering Calculations:

- Technical Specification (Limiting Values)
  - System Performance Criteria
  - Equipment Selection for:
    - Regulatory and Standards Compliance
    - Procurement

- Protection, Control and Instrumentation (PCI) Setting
  - Primary PCI settings
  - Backup PCI settings
  - Protection Zones Coordination settings

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Levels of Fault Calculations:

- Limiting Value @ PCC
  - Limited by technical ratings of commercially available equipment

- PCI Value
  - Actual Fault Level at PCC

Short Circuit (SC) values at PCC are provided by Grid Owners; however, in the absence of such data, the Engineer must be able to determine the most appropriate SC value to be used in the Limiting Value calculation to be able to write the specification of the design work.

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1. Determine and select Earth Conductor Size, using Equation 37 of IEEE 80-2000:

$$I = A_{mm^2}\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_c \alpha_r \rho_r}\right)\ln\left(\frac{K_o + T_m}{K_o + T_a}\right)}$$

Where:

I	-	Three Phase Short Circuit RMS Current, kA
A_{mm2}	-	***Minimum*** Conductor Cross Section, mm^2
TCAP	-	Thermal Capacity per Unit Volume, $J/cm^3.°C$
t_c	-	Duration of Short Circuit Current, second
α_r	-	Thermal Coefficient of Resistivity at Reference Temp, 1/°C
ρ_r	-	Resistivity of Earth Conductor at Reference Temp, υΩ-cm
$1/\alpha_o$	-	$K_{o,}$ °C
Tm	-	Max Allowable(Fusing) Temp, °C
Ta	-	Ambient Temp, °C
T_r	-	Reference Temp for Material Constant, °C

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2. Calculate Earth Grid Resistance

2.1 Determine and Set Earth Grid Arrangement; parameters to be set are:

- n_r or r - No of Rows
- L_g - Length of Row
- n_c or c - No. of Column
- W_g - Length of Column, meter
- L_c - Total Length of Earth Conductor, meter
- L_p - Length of Perimeter, meter
- Conductor Size as determined from step 1
- D - Cross Sectional Diameter of earth conductor, meter
- Number of Electrodes
- Earthing Electrode Length - normally 3 meters
- L_R - Total Length of Earthing Electrode, meter
- L_T - Total Length of Buried Conductors, meter

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2.2 Calculate Surface Layer Derating Factor, as per Equation 27 of IEEE 80-2000:

$$C_s = 1-(0.09(1-\rho/\rho s)/(2hs+0.09))$$

Where:

ρ	-	Soil Resistivity, Ω-m
ρ_s	-	Resistivity of Surface Material, Ω-m
h_s	-	Thickness of Surface Layer, meter
C_s	-	Surface Layer Derating Factor

2.3 Calculate Earthing Grid Resistance, as per Equation 52 of IEEE 80-2000:

$$Rg=\rho[1/Lt+(1/\sqrt{}20A)*(1+(1/((1+h*\sqrt{}20/A))]$$

Where:

h	-	Depth of Conductor, meter
A	-	Area Occupied by Conductor, m^2
R_g	-	Earth Grid Resistance,

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3. Calculate Maximum Grid Current

3.1 Calculate Maximum Symmetrical Earth Fault Current

$$I_g = (I_{o\ max}) \times S_f$$

Where:

- $I_{o\ max}$ - Max Symmetrical Earth fault Current
- S_f - Current Division Factor
- I_g - Symmetrical Grid Current

3.2 Calculate DC Time Offset, as per Equation 74 of IEEE 80-2000:

$$T_A = \frac{X}{R} \cdot \frac{1}{2\pi f}$$

Where:

- X/R - X/R Ratio at Fault
- f - Frequency
- T_A - DC Time Offset, T_a

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3.3 Calculate Decrement Factor, as per Equation 79 of IEEE 80-2000:

$$D_f = \sqrt{1 + \frac{T_a}{t_f}\left(1 - e^{\frac{-2t_f}{T_a}}\right)}$$

Where:

- T_a - DC Time Offset
- t_c or t_f - Time duration of Fault
- D_f - Decrement Factor

3.4 Calculate Max Earth Grid Current:

$$I_G = I_g \times D_f$$

Where:

- I_g - Symmetrical Grid Current
- D_f - Decrement Factor
- I_G - Maximum Earth Grid Current

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4. Calculate Voltage Gradient Limits

4.1 Calculate Maximum Tolerable Touch Potential:

For 50kg:

$$E_{touch,50} = (1000 + 1.5C_s\rho_s)\,\frac{0.116}{\sqrt{t_s}}$$

For 70kg:

$$E_{touch,70} = (1000 + 1.5C_s\rho_s)\,\frac{0.157}{\sqrt{t_s}}$$

Where:

- C_s - Surface Layer Derating Factor
- ρ_s - Resistivity of Surface Material, Ω-m
- t_s - Time duration of Fault

4.2 Calculate Maximum Step Potential:

For 50kg:

$$E_{step,50} = (1000 + 6C_s\rho_s)\,\frac{0.116}{\sqrt{t_s}}$$

For 70kg:

$$E_{step,70} = (1000 + 6C_s\rho_s)\,\frac{0.157}{\sqrt{t_s}}$$

Where:

- C_s - Surface Layer Derating Factor
- ρ_s - Resistivity of Surface Material, Ω-m
- t_s - Time duration of Fault

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4.3 Calculate Earth Potential Rise:

$$GPR = I_G \times R_g$$

Where:

- I_G - Maximum Earth Grid Current
- R_G - Earth Grid Resistance, *using the value as at Step 2.3*
- GPR - Ground Potential Rise – as calculated

4.4 Calculate Earth Potential Limit:

$$GPR = I_G \times R_g$$

Where:

- I_G - Maximum Earth Grid Current
- R_G - Earth Grid Resistance; *using the max value as allowed by technical specifications*
- GPR - Ground Potential Rise Limit

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4.5 Earth Design Validation and Verification

Touch Voltage Criteria:

Calculated GPR < $E_{touch\ limit}$; Earth Grid Design is SAFE

Step Voltage Criteria:

Calculated GPR < $E_{step\ limit}$; Earth Grid Design is SAFE

If the above voltage limits of Etouch and Estep are not met, the earthing design must continue to Step 5 and beyond.

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5 Earth Grid Design Verification

5.1 Calculate Geometric Factor “n”, as per Equation 84 of IEEE 80-2000:

$$n = n_a \times n_b \times n_c \times n_d$$

5.1.1 Calculate Geometric Factor “n_a”, as per Equation 85 of IEEE 80-2000:

$$n_a = \frac{2L_c}{L_p}$$

5.1.2 Calculate Geometric Factor “n_b”, as per Equation 86 of IEEE 80-2000:

$$n_b = \sqrt{\frac{L_p}{4\sqrt{A}}}$$

Where:

- L_c - Total Length of Conductor
- L_p - Length of Grid Conductor on the perimeter
- n_a - Geometric Factor
- n_c - 1.0
- n_d - 1.0
- A - area of earth grid

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5.2 Calculate Average Spacing Between Parallel Grid Conductors:

$$D = \frac{1}{2}\left(\frac{W_g}{n_r - 1} + \frac{L_g}{n_c - 1}\right)$$

Where:

- n_r - No of Rows
- L_g - Length of Row
- n_c - No. of Column
- W_g - Length of Column, meter

5.3 Calculate Weighing Factor for Depth of Burial:

$$k_h = \sqrt{(1+h)}$$

Where:

- h - depth of conductor
- k_h - Weighing Factor for Depth Burial

5.4 Weighing Factor for Earth Electrode = 1; for electrodes along the earth grid perimeter

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5.5 Calculate Geometric Mean Spacing, as per Equation 81 of IEEE 80-2000:

$$K_m = \frac{1}{2\pi}\left(\ln\left[\frac{D^2}{16h \times d} + \frac{(D+2h)^2}{8D \times d} - \frac{h}{4d}\right] + \frac{K_{ii}}{K_h}\ln\left[\frac{8}{\pi(2n-1)}\right]\right)$$

Where:

D	-	Spacing Between Parallel grid Conductors, meters
h	-	Depth of Buried Grid Conductors, meter
d	-	Cross Sectional Diameter of earth grid conductor
k_h	-	Weighting Factor for depth of Conductor
k_{ii}	-	Weighting Factor for Electrodes on corner mesh
n	-	Geometric factor
K_m	-	Geometric Mean Spacing

5.6 Calculate Irregularity Factor, as per Equation 89 of IEEE 80-2000:

$$K_i = 0.644 + 0.148n$$

Where:

n	-	Geometric factor
K_i	-	Irregularity Factor

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5.7 Calculate Effective Buried Length of Earth Grid – for Mesh Voltage:

$$L_M = L_c + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right] L_R$$

Where:

- L_M - Effective Buried Length of grid conductors, meter
- L_C - Total Length of Conductor, meter
- L_r - Length Earth Electrode
- L_x - Length of Earth Grid Row
- L_y - Length of Earth Grid Column
- L_R - Total Length of Earth Electrode

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5.8 Calculate Maximum Mesh Voltage:

$$E_m = \frac{\rho_s K_m K_i I_G}{L_M}$$

Where:

- ρ_s - Soil Resistivity
- K_m - Geometric Mean Spacing
- K_i - Irregularity Factor
- I_G - Maximum Earth Grid Current
- L_M - Effective Buried Length, for mesh voltage
- E_m - Maximum Mesh Voltage

5.9 Calculate Geometric Mean Spacing Factor, as per Equation 94 IEEE 80-2000:

$$K_s = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}\left(1 - 0.5^{n-2}\right)\right]$$

Where:

- h - Depth of Conductor h
- D - Average Spacing between Parallel Grid Conductor D
- n - Geometric Factor, n n
- K_s - Geometric Spacing Factor

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5.10 Calculate Effective Buried Length of Earth Grid – for Step Voltage:

$$L_S = 0.75L_c + 0.85L_R$$

Where:

L_c - Total Length of Conductor
L_R - Total Length of Earthing Electrode
L_s - Effective Buried Length - For Step Voltage

5.11 Calculate Step Voltage, as per Equation 92 IEEE 80-2000:

$$E_s = \frac{\rho_s K_s K_i I_G}{L_S}$$

Where:

ρ_s - Soil Resistivity
K_S - Geometric Spacing Factor
K_i - Irregularity Factor
I_G - Maximum Earth Grid Current
L_s - Effective Buried Length, for Step Voltage
E_s - Step Voltage

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5.12 Earth Grid Design Validation and Verification:

<u>Touch Voltage Criteria:</u>

Mesh Voltage (Em) < Maximum Tolerable Touch Voltage (E_{touch})

Earth Grid Design is SAFE

<u>Step Voltage Criteria:</u>

Step Voltage (Es) < Maximum Tolerable Step Voltage (E_{step})

Earth Grid Design is SAFE

If the above voltage limits of Etouch and Estep are not met, the earthing design must be revised to review values and assumptions on:

- ***Time duration of fault***
- ***Maximum symmetrical fault value***
- ***Soil Resistivity; depth of earth conductor***
- ***Surface Layer Resistivity and thickness; wet or dry assumptions***
- ***X/R Ratio of system at PCC***
- ***Required earth resistance***
- ***Area covered by earth grid***

Short Resume

Adelino V. Garcia, Jr.
Professional Electrical Engineer – 1584

Chairman and President
AVGarcia Power Systems, Corp.
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President
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Technical Director
Caraga Renewable Energy Corp.

Chairman
Alto Verde Corp.

Chairman
Ballesteros Memorial Park

40 Years of Energy Systems Engineering and Integration
Project Management, Execution and Implementation
Business Development and Management

Short Resume
Adelino V. Garcia Jr. PEE

<u>Expertise and Qualifications:</u>

- Energy Engineering and Systems Integration of various technologies such as: Coal Thermal; Combustion Gas Turbine; Heavy/Light Fuel Oil; Biomass and Biogas; Hydroelectric, Solar PV, Wind and Fuel Cell Energy Generation Facilities
- Business and Project Development of Conventional and Renewable Energy Generation Technologies

Short Resume
Adelino V. Garcia Jr. PEE

Expertise and Qualifications:

- Project Development, Design and Engineering, Project Execution and Management, Operation and Maintenance of various Power Generation Facilities (PGFs) Technologies:
  - More than 3,000MW of Coal: Thermal and Gasification
  - More than 1,500MW of HFO/LFO Diesel: Low; Medium; High Speed
  - More than1200MW Combustion Turbine: Simple and Combined Cycle
  - More than 100MW of Biomass/Biogas: Thermal; Pyrolysis; Anaerobic
  - More than 100MW of Hydroelectric: Run-of-River; Pump Storage
  - More than 100MW of Solar: PV and Concentrating
  - More than 50MW of Fuel Cell (Hydrogen Technology): Molten Carbonate
  - More than 100MW of Kinetic Power: CAES + Buoyancy

Short Resume
Adelino V. Garcia Jr. PEE

Expertise and Qualifications:

- Engineering and Execution of Grid Connection Facilities for PGFs:
    - 2000MW of 500kV Switchyards
    - 1,500MW of 230kV Switchyards
    - 1,000MW of 115/138kV Switchyards
    - 1,000MW of 72kV Switchyards & Substations
    - 100MW of 36kV Switchyards & Substations
    - 100MW of 15kV Switchyards & Substations

Q & A

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