

Technical Paper · U.S. Market Edition

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Grounding Grid and Ground-Fault Protection Compatibility

U.S. practice (IEEE 80 · 2778 · C37.112) · Case: 2.5 MWac PV plant POI

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Abstract

This technical paper presents a method to check whether the grounding grid at the point of interconnection (POI) of a photovoltaic (PV) plant is compatible with the ground-fault protection that actually clears faults there. The touch-voltage criterion of IEEE Std 80 [1] is split into two quantities with the same unit ($A \cdot s^{1/2}$): the demand imposed by the fault and the protection, $K_{TH} = I_G \cdot \sqrt{t_f}$, and the capacity of the grid with its surface layer, K_{THM}. Both are drawn on the 50N/51N coordination chart together with the Human Tolerance Curve (CTH), following Alves and Franco [15] and Lance and Boulton [16].

The method is applied to an anonymized 2.5 MWac distributed PV plant interconnected to a 34.5 kV utility feeder. The grid figure G = 4.74 S comes from the plant-wide grounding model. With 4 in of crushed rock and the 50 kg criterion, the grid capacity at the POI switchgear is K_{THM} = 2,419 $A \cdot s^{1/2}$. A ground fault on the plant side of the protection CTs is cleared by the plant relay in 0.090 s (K_{THM}/K_{TH} = 1.91, **PASS**). A fault on the utility side of those CTs — incoming terminations, arresters and revenue metering — is seen only by the utility feeder relay and is cleared in 0.741 s; the demand K_{TH} = 3,042 $A \cdot s^{1/2}$ exceeds the grid capacity (ratio 0.80, **FAIL**). The longest clearing time the grid accepts for that fault is 0.45 s. The 0.20 s assumed in the grid design does not show this result.

The paper lists four mitigation options for discussion, the common errors found when grounding and protection studies are done separately, and the minimum content of a compatibility check. A companion spreadsheet reproduces the calculation and the chart. The paper and the spreadsheet are educational and screening references; they do not replace a site-specific study prepared, signed and sealed by a licensed Professional Engineer.

Keywords: grounding grid, touch voltage, IEEE 80, IEEE 2778, ground-fault protection, 50N/51N, protection coordination, human tolerance curve, PV plant, point of interconnection.

Notice – professional responsibility

Educational content. This paper describes an engineering method and illustrates it with an anonymized example. It is not an engineering study, design, specification or recommendation for any specific project.

No professional responsibility. Solstice Performance Solutions LLC d/b/a Solstice Energy does not provide services that require professional engineering licensure in the United States and assumes no technical or professional responsibility for designs, studies, settings or decisions based on this paper or on the companion spreadsheet.

Engineer of Record. Any grounding study, protection coordination study or compatibility check for a real installation must be prepared, signed and sealed by a Professional Engineer (PE) licensed in the jurisdiction where the project is located, who is responsible for the data, the assumptions, the method and the results, and for compliance with the applicable codes and with the requirements of the utility and of the authority having jurisdiction (AHJ).

No warranty. The information is provided as is. Standards, utility requirements and site conditions change; the reader is responsible for verifying every value against the current editions and the project data.

1 Introduction and Scope

Grounding design and protection coordination are usually separate deliverables, often prepared by different engineers. Both depend on the same two numbers: the ground-fault current and the time it takes to clear it. IEEE 80 places the clearing time t_f in the denominator of the tolerable touch voltage, but the grid designer normally assumes a value, typically 0.2 to 0.5 s, instead of taking it from the relay settings. When the assumption is not checked, a grid can be approved for a clearing time that no protective device achieves.

At a PV plant the risk concentrates at the POI switchgear. It receives the full utility fault current, people operate and read meters there, and part of its equipment sits upstream of the plant's own protection CTs, where only the utility can clear a fault.

Scope: this paper covers the touch-voltage compatibility check between the grounding grid and the ground-fault protection (50N/51N) at the POI switchgear of a PV plant. It does not cover the grid design itself, step voltage, transferred potentials or arc-flash hazard, which are separate studies.

Audience: grounding, protection and interconnection engineers, and owner's and independent engineers who review grounding and protection studies.

Normative basis: IEEE Std 80 for the safety criterion, IEEE Std 2778 for PV plants, IEEE C37.112 for the relay curves and IEEE Std 1547 for the interconnection. Section 3 lists each document and what it contributes.

Case data: the plant data in Section 4 are anonymized and adapted to U.S. practice. They are representative of the original engineering study and do not identify the site, the owner or the utility.

Professional responsibility: the method and the example are for education and screening. Applying them to a real project, including the choice of criteria, data and mitigation, is the responsibility of the Engineer of Record, a Professional Engineer licensed in the jurisdiction of the project (see the notice after the abstract).

2 Fundamentals of the Method

2.1 Tolerable touch voltage

IEEE 80 limits the body current to $I_B = k/\sqrt{t_s}$, with k = 0.116 for a 50 kg person and k = 0.157 for a 70 kg person. With a body resistance of 1,000 Ω and the foot resistance corrected for the surface layer, the tolerable touch voltage for a fault cleared in t_f seconds is:

$$E_{touch} = (1000 + 1.5 \cdot C_s \cdot \rho_s) \cdot k \;/\; \sqrt{t_f} \qquad (1)$$

$$C_s = 1 - 0.09\cdot(1 - \rho/\rho_s) \;/\; (2\cdot h_s + 0.09) \tag{2}$$

where ρ is the resistivity of the upper soil layer and ρ_s and h_s are the resistivity and thickness of the surface layer. The criterion assumes a person touching a grounded structure with the left hand, with both feet together 1 m (3.3 ft) away. The current path from the left hand to the feet passes close to the heart and is the most critical one.

2.2 Separating protection demand from grid capacity

The worst touch voltage in the area, the mesh voltage E_m, is proportional to the current injected into the grid, I_G. Writing $E_m \le E_{touch}$ and moving the time to the left side separates what the protection imposes from what the grid withstands:

$$K_{TH} = I_G\cdot\sqrt{t_f} \;\le\; K_{THM} = k\cdot(1000 + 1.5\cdot C_s\cdot\rho_s)\cdot G \tag{3}$$

$$I_G = C_p\cdot D_f\cdot S_f\cdot I_f \;;\;\; D_f = \sqrt{[1 + (T_a/t_f)\cdot(1 - e^{-2t_f/T_a})]} \;;\;\; T_a = (X/R)/\omega \tag{4}$$

where I_f is the symmetrical rms ground-fault current, C_p the projection factor for future growth, S_f the current division factor and D_f the decrement factor for the dc offset.

- **K_{THM} – capacity of the grid:** the maximum product current × √time that the grid, with its surface layer, accepts without the touch voltage exceeding the tolerable limit. It depends only on the design (geometry, soil, surface layer and body-weight criterion) and is independent of the fault current and of the relay settings.
- **K_{TH} – demand:** the current actually injected into the grid multiplied by the square root of the time the protection takes to clear it. It depends only on the system and on the protection (I_f, C_p, D_f, S_f and t_f) and is independent of the grid.

Squaring both sides shows the physical meaning. K_{TH}^2 is the I^2t let through by the fault and the protection; K_{THM}^2 is the I^2t that the grid accepts before the energy delivered to the body reaches the fibrillation threshold. When the check fails, either the capacity is raised (grid or surface layer) or the demand is reduced (faster clearing).

2.3 Grid figure G from the grounding model

In the simplified method of IEEE 80, $G = L_M/(\rho\cdot K_m\cdot K_i)$. It is measured in siemens: the current injected per volt of mesh voltage. The simplified method does not represent multilayer soil, irregular geometry or the bonding of the POI grid to the array grid, so it is not suitable for PV plants. Because the touch voltage is linear in I_G, G is taken from the grounding software run:

$$G = I_{G,sim} \;/\; E_{touch,max,sim} \tag{5}$$

where $I_{G,sim}$ is the current injected in the simulation and $E_{touch,max,sim}$ the maximum touch voltage found in the area analyzed.

2.4 Human Tolerance Curve and grid point

The CTH uses the Biegelmeier–Lee limits [17]: 50 mA, which the body withstands for long periods (BL1), and 500 mA, the fibrillation threshold for very short shocks (BL2). For each limit $t_{BL} = (k/I_{BL})^2$, which gives 5.38 s and 0.054 s for 50 kg. On the coordination chart the CTH is drawn in fault-current terms, $I = K_{TH}/(S_f \cdot D_f(t) \cdot \sqrt{t})$, between BL1 and BL2, and extended vertically above BL1 and below BL2. By construction it passes through the fault clearing point ($C_p \cdot I_f$, t_f).

The grid is represented by one point at t_f, with current $I = K_{THM}/(S_f \cdot D_f \cdot \sqrt{t_f})$: the fault current that would make the touch voltage equal to the tolerable value. The grid is validated when this point lies to the right of the CTH.

2.5 Grid limit curve

The CTH checks a single design point. This paper also draws the grid limit curve, $I_{lim}(t) = K_{THM}/(S_f \cdot D_f(t) \cdot \sqrt{t})$, parallel to the CTH and through the grid point. For every fault current up to $C_p \cdot I_f$, the clearing time of the device that sees the fault must stay below this curve. This checks the whole relay curve, including faults with fault resistance.

2.6 Acceptance criterion

The grid is compatible with the protection when, for every fault location and the device that clears it:

$$\mathrm{K_{THM}} \;/\; \mathrm{K_{TH}} > 1 \tag{6}$$

The result is reported as **PASS** when Eq. (6) holds and **FAIL** otherwise. The report also gives the longest clearing time the grid accepts, $t_{f,max}$, the solution of $C_p \cdot D_f(t) \cdot S_f \cdot I_f \cdot \sqrt{t} = K_{THM}$.

3 Standards and References Applicable (U.S. Market)

The documents below form the basis of the method. Always check each standard against its most recent edition before citing an edition, item or clause in a report.

Normative documents

Document	What it provides for this analysis
IEEE Std 80-2013	Tolerable body current, touch and step voltage criteria, surface layer factor C_s, maximum grid current (D_f, S_f, C_p) and the simplified mesh voltage. Basis of Eqs. (1) to (5).
IEEE Std 2778-2020	Grounding of solar power plants for personnel protection. Applies the IEEE 80 principles to PV arrays, collection systems and substations.
IEEE Std 81-2012	Measurement of soil resistivity and ground impedance. Source of the soil model and of the post-construction verification.

Document	What it provides for this analysis
IEEE Std 367-2012	Ground potential rise and fault current distribution. Supports the current division factor S_f.
IEEE Std 665-1995	Grounding of generating stations.
IEEE Std 142-2007	Grounding of industrial and commercial power systems (Green Book).
IEEE C37.112-2018	Inverse-time characteristics of overcurrent relays. Curve equations of the 51N elements.
IEEE C37.2-2022	Device function numbers (50N, 51N, 52).
IEEE C37.230-2020	Protective relay applications to distribution lines: feeder ground protection and reclosing.
IEEE Std 1547-2018 / 1547a-2020	Interconnection of distributed energy resources. Protection coordination with the Area EPS and grounding at the POI.
NFPA 70 (NEC) 2023	Art. 250 (grounding and bonding) and Art. 691 (large-scale PV electric supply stations).
ANSI/IEEE C2 (NESC) 2023	Grounding methods (Section 9) and electric supply stations.
NFPA 70E-2024	Electrical safety in the workplace. It does not set touch-voltage limits for fault conditions; those come from IEEE 80.

3.1 How to use these documents together

- **IEEE 80** and **IEEE 2778** define the safety criterion and how to model the grid.
- **IEEE 81** provides the soil data; the grounding software turns them, with the grid geometry, into the figure G.
- **IEEE C37.112** and the relay settings of the plant and of the utility give t_f for each fault location. **IEEE 1547** and the utility interconnection requirements define which device protects each part of the POI.
- This method joins the two studies. It does not replace the grid study or the coordination study.

3.2 Reference values

IEEE 80 gives criteria for 50 kg and 70 kg persons. This paper uses 50 kg at the POI switchgear, which is the conservative choice. The criterion for each project is defined by the Engineer of Record and must be stated in the report, because it can change the verdict (Section 7). For crushed rock, 3,000 Ω·m is a common design value for clean wet rock; the value should be confirmed by testing the material actually supplied.

4 Case Data

4.1 Plant and point of interconnection

Plant and POI (anonymized)

Item	Value
Plant	PV plant, 2.5 MWac, distributed generation
Interconnection	34.5 kV, 60 Hz, three-wire utility distribution feeder
Step-up transformers	34.5 kV delta – 800 V grounded wye. The delta winding faces the utility, so the plant contributes no zero-sequence current to a 34.5 kV ground fault.
POI switchgear	Incoming terminations and arresters, utility revenue metering (CTs/VTs), load-break disconnect, protection CTs 200:5, multifunction relay 50N/51N, vacuum breaker (3-cycle)
Grounding	POI switchgear grid bonded to the plant-wide array grid

4.2 Fault data

Ground-fault data at the POI

Parameter	Value	Note
SLG fault current, symmetrical (I_f)	2,980 A	utility short-circuit data
X/R ratio	17.8 (T_a = 47.2 ms)	for D_f
SLG fault current with 40 Ω ($I_{f,min}$)	487 A	utility short-circuit data
Projection factor C_p	1.15	future fault growth
Current division factor S_f	1.0	three-wire feeder: all ground current returns through earth (conservative)
Fault current for timing, $C_p \cdot I_f$	3,427 A	

4.3 Soil, surface layer and person

Safety parameters

Parameter	Value	Note
Soil resistivity, upper layer ρ	642 Ω·m	uniform model used in the grid study
Crushed rock ρ_s / h_s	3,000 Ω·m / 0.10 m (4 in)	wet value
Surface layer factor C_s	0.756 ($C_s \cdot \rho_s$ = 2,268 Ω·m)	Eq. (2)
Body-weight criterion	50 kg (k = 0.116)	conservative
E_{touch} at 0.20 s (reference)	1,142 V with rock / 509 V bare soil	Eq. (1)

4.4 Grounding grid model

The grid was modeled plant-wide in a commercial grounding package, with the POI switchgear grid bonded to the array grid. In the simulation, $I_{G,sim}$ = 3,600 A produced a maximum touch voltage of 760 V in the POI switchgear area. From Eq. (5), G = 3,600/760 = **4.74 S**.

4.5 Ground-fault protection

Ground-fault protection settings (primary amperes)

Item	Plant relay (POI switchgear)	Utility feeder relay
Functions	50N / 51N	51N
Curve (IEEE C37.112)	Moderately Inverse	Moderately Inverse
51N pickup / time dial	15 A / TD 0.90	80 A / TD 0.85
50N pickup / operating time	150 A / 40 ms	not used
Breaker interrupting time	3 cycles (0.050 s)	5 cycles (0.083 s)
Clearing time at $C_p \cdot I_f$ = 3,427 A	0.090 s	0.741 s

Utility settings are those provided for the interconnection study. Reclosing of the utility feeder is not modeled (see Section 7).

5 Fault Scenarios at the POI Switchgear

The position of the fault relative to the plant protection CTs decides which device clears it and therefore the real t_f (Figure 1). Three scenarios are checked:

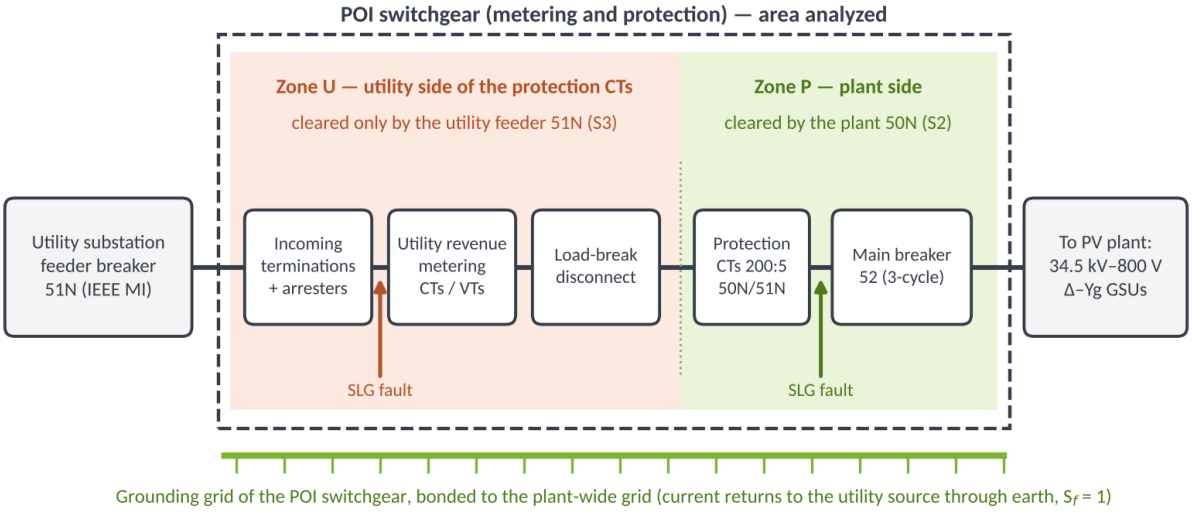


Figure 1. POI switchgear: zone cleared only by the utility (U) and zone cleared by the plant relay (P).

- **S1 – grid design assumption:** t_f = 0.20 s, the value assumed in the grid study.
- **S2 – plant-side fault (zone P):** main breaker and outgoing terminations. The plant 50N operates for any current above 150 A: t_f = 0.090 s.
- **S3 – utility-side fault (zone U):** incoming terminations, arresters, revenue metering CTs/VTs and disconnect. The plant relay does not see the current; only the utility feeder 51N clears it: t_f = 0.741 s.

6 Results

6.1 Demand and capacity

Demand K_{TH} per scenario

Scenario	t_f (s)	D_f	I_G (A)	K_{TH} (A·s$^{1/2}$)	Touch voltage I_G/G (V)
S1 – design assumption	0.200	1.112	3,810	1,704	804
S2 – plant side (50N)	0.090	1.230	4,215	1,265	890
S3 – utility side (51N)	0.741	1.031	3,535	3,042	746

Capacity K_{THM} of the grid at the POI switchgear

Surface	k·(1000 + 1.5·C_s·ρ_s) (V·s$^{1/2}$)	K_{THM} (A·s$^{1/2}$)	$t_{f,max}$ at C_p·I_f (s)
Crushed rock, 4 in	510.7	2,419	0.451
Bare soil	227.7	1,079	0.056

Verification, K_{THM}/K_{TH} (PASS when > 1)

Scenario	Crushed rock	Bare soil	Tolerable touch with rock at t_f (V)
S1 – design assumption	1.42 – PASS	0.63 – FAIL	1,142
S2 – plant side (50N)	1.91 – PASS	0.85 – FAIL	1,702
S3 – utility side (51N)	0.80 – FAIL	0.35 – FAIL	593

In S3 the expected touch voltage, 746 V, is above the tolerable 593 V for a 0.741 s exposure. The same fault cleared in 0.090 s on the plant side produces 890 V against a tolerable 1,702 V.

6.2 Coordination charts

Figures 2 and 3 show the relay curves, the CTH, the grid limit curves and the grid points for S2 and S3.

In Figure 2 the plant 50N clears the fault far below the grid limit with crushed rock. On bare soil the grid point falls on the left of the CTH, so the rock is required even when the plant relay clears the fault. In Figure 3 the utility curve crosses the grid limit with crushed rock at about 2.65 kA (0.78 s); every fault above that current, up to $C_p \cdot I_f$, is cleared too slowly.

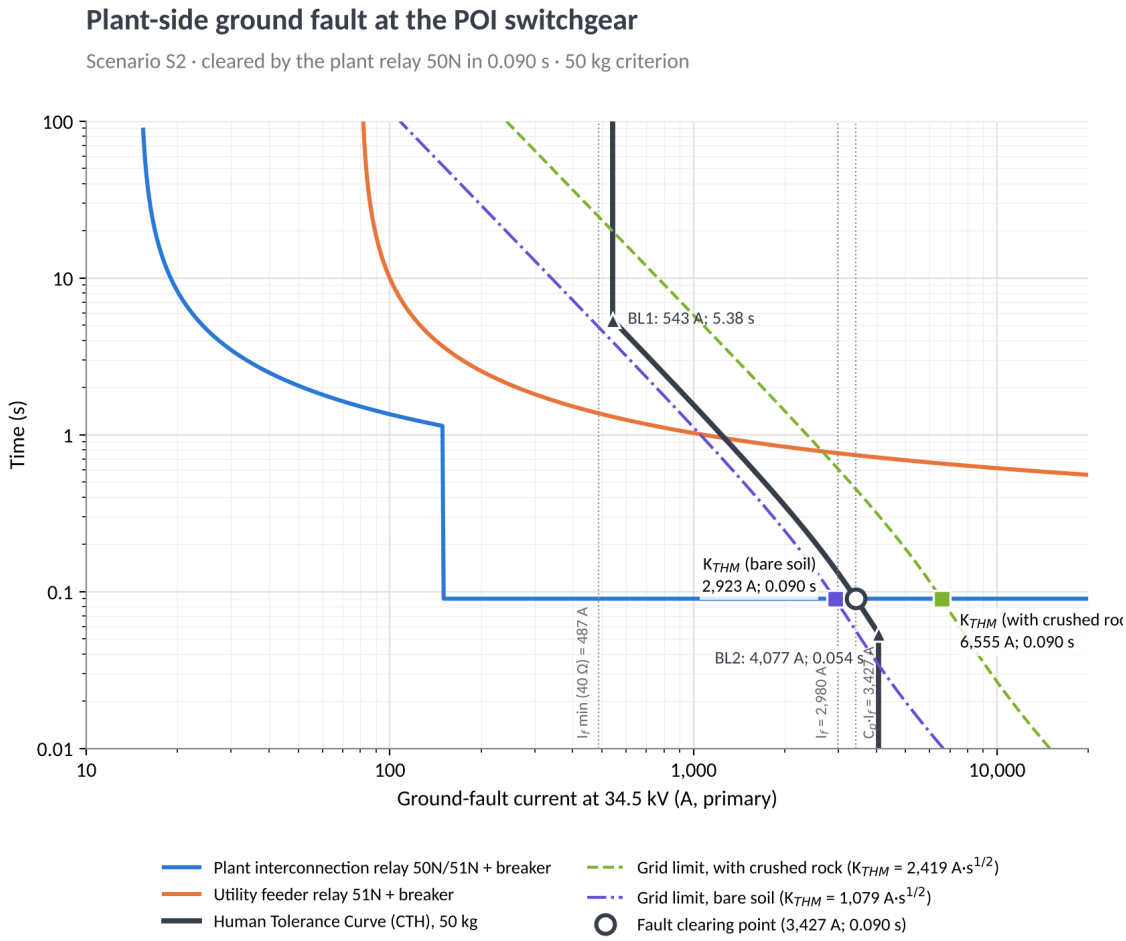


Figure 2. Plant-side fault (S2): the grid point with crushed rock lies to the right of the CTH (PASS).

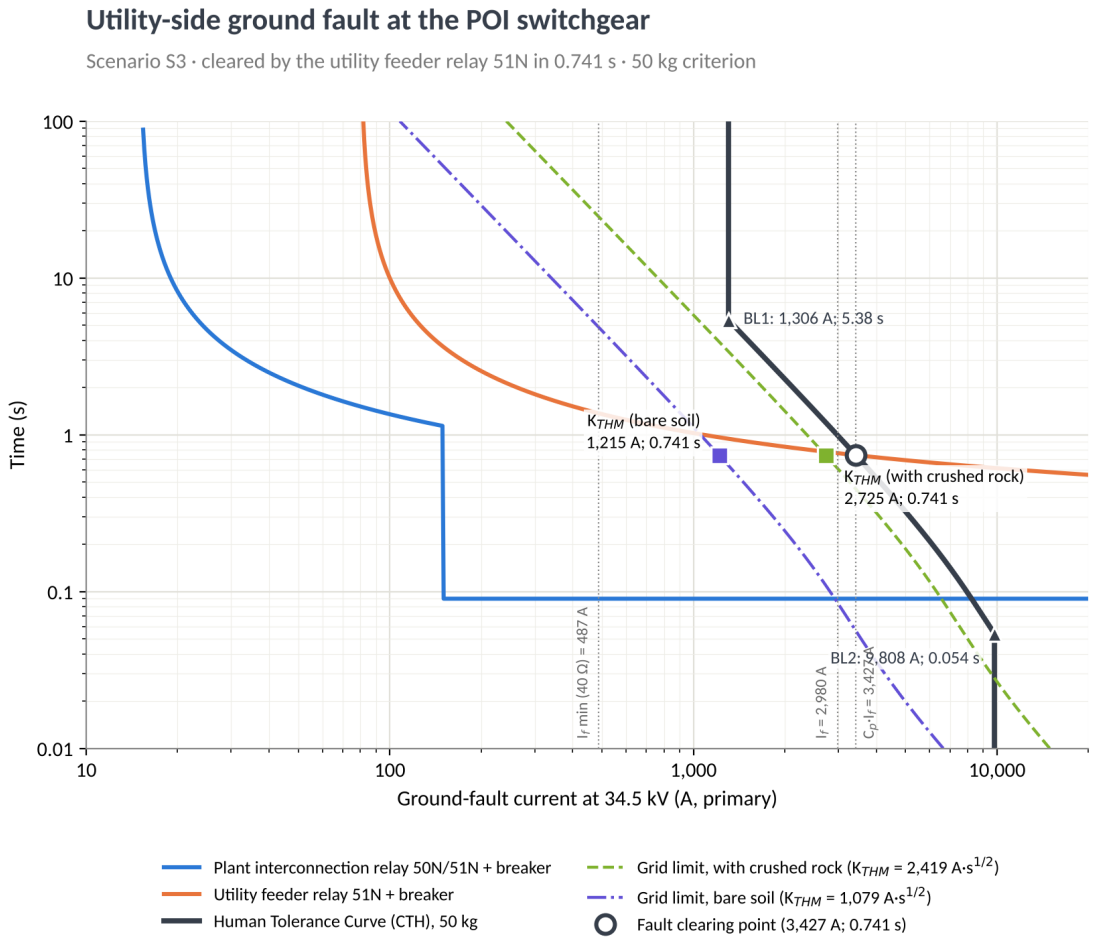


Figure 3. Utility-side fault (S3): the grid point with crushed rock lies to the left of the CTH (FAIL).

6.3 Full-curve check

- **Plant relay, crushed rock:** below the grid limit over the whole range up to $C_p \cdot I_f$.
- **Utility relay, crushed rock:** above the grid limit from about 2,654 A to 3,427 A.
- **Bare soil:** the plant 50N exceeds the limit above about 2,923 A and the utility relay above about 1,050 A.
- **High-resistance fault (40 Ω, 487 A):** the utility clears it in 1.37 s; K_{TH} = 667 A·s$^{1/2}$, well below the grid capacity.

7 Notes on the Results and Mitigation

1. The grid was approved for an assumed t_f of 0.20 s. The real clearing times are 0.090 s on the plant side and 0.741 s on the utility side. The assumption is conservative for the plant side and optimistic for the utility side, which is where the risk is highest.

2. In this example the crushed rock is a requirement, not a margin: on bare soil no scenario passes. Its extent is defined by the Engineer of Record; typically it covers the area within reach of any grounded metal part of the switchgear (doors, enclosures, fence and gates) and extends at least 1 m (3 ft) beyond it.
3. In this example, any one of the following measures would resolve S3. They are presented for discussion only; the selection, design and verification of any measure are the responsibility of the Engineer of Record:

- **Faster clearing on the utility side:** 0.45 s or less at 3,427 A, for example a utility-owned recloser at the POI, upstream of the switchgear, with a fast ground element. This requires agreement with the utility.
- **Higher-resistivity surface:** $C_s \cdot \rho_s \geq 3{,}024\ \Omega\cdot m$. Washed crushed rock with $\rho_s \geq 5{,}000\ \Omega\cdot m$ and 4 in gives $K_{THM} \approx 3{,}556\ A\cdot s^{1/2}$ (ratio 1.17). Asphalt is another option.
- **Local grid reinforcement:** reduce the maximum touch voltage at the switchgear from 760 V to 604 V or less at 3,600 A ($G \geq 5.96$ S), with a perimeter ring 1 m outside the enclosure, closer meshes and corner rods, confirmed in the grounding software.
- **Current division:** if the feeder is four-wire multigrounded and its neutral is bonded to the POI grid, $S_f < 1$ (IEEE 80 Annex C, IEEE 367). $S_f \leq 0.80$ would be enough, but it must be calculated with the utility's network data, never assumed.

4. If the utility feeder recloses onto a permanent fault, the exposures add up. For short reclosing intervals, IEEE 80 recommends considering the combined duration of successive shocks. The reclosing sequence should be requested with the settings.
5. With the 70 kg criterion, S3 would pass ($K_{THM} = 3{,}274\ A\cdot s^{1/2}$, ratio 1.08). The body-weight criterion changes the verdict, so it must be stated explicitly and checked in the software output.

8 Common Errors and Best Practices

Common error	Effect on the result	Best practice
Assuming t_f in the grid study without checking the relays	Grid approved for a time no device achieves	Take t_f from the coordination study for each fault location
Using only the plant relay to define t_f	Faults upstream of the plant CTs are ignored	Identify the zone cleared only by the utility
Using the asymmetrical current together with D_f	DC offset counted twice	Use the symmetrical rms current and D_f
Stating 50 kg and calculating with 70 kg	Tolerable voltages about 35% too high	Check k in the software output
Treating crushed rock as optional	Touch criterion not met on bare soil	Specify area, thickness and minimum resistivity

Common error	Effect on the result	Best practice
Checking only the bolted fault	Slow part of the relay curve not checked	Full-curve check up to $C_p \cdot I_f$
Ignoring reclosing	Exposure time underestimated	Request the reclosing sequence from the utility
Assuming $S_f < 1$ without data	Demand underestimated	Calculate S_f with IEEE 80 Annex C or IEEE 367

8.1 Quick checklist

- Fault data: symmetrical SLG current, X/R, C_p and S_f, with sources.
- Body-weight criterion and surface layer (resistivity, thickness, extent).
- Grid figure G from the grounding model of the area analyzed.
- Relay settings of the plant and of the utility, breaker times and reclosing.
- One check per fault location: plant side and utility side of the protection CTs.
- K_{TH}, K_{THM}, ratio, $t_{f,max}$ and the full-curve check reported for each case.
- Study prepared, signed and sealed by the Engineer of Record (licensed PE).

9 Minimum Report Content

The report must allow another engineer to repeat the check with the same data. Recommended minimum content:

- **Identification:** plant, POI, area analyzed, Engineer of Record (name, license number and jurisdiction) and reviewer.
- **Fault data:** I_f, X/R, $I_{f,min}$, C_p, S_f and their sources.
- **Safety parameters:** body-weight criterion, soil model, surface layer and C_s.
- **Grid:** software, model, $I_{G,sim}$, maximum touch voltage and G.
- **Protection:** devices, curves, settings, breaker times and reclosing, with sources.
- **Results:** K_{TH} and K_{THM} for each scenario, ratio, $t_{f,max}$, coordination charts and the full-curve check.
- **Limitations:** assumptions, items to be confirmed by the utility and mitigation adopted.
- **Professional seal:** signature and seal of the Engineer of Record licensed in the jurisdiction where the project is located.

Notice

This paper is educational. Solstice Energy assumes no technical or professional responsibility for its application. Every study for a real installation must be prepared, signed and sealed by a Professional Engineer licensed in the jurisdiction of the project.

References

Always check each standard against its most recent edition before citing it in a formal document.

Standards (U.S. market)

1. IEEE Std 80-2013, *IEEE Guide for Safety in AC Substation Grounding*.
2. IEEE Std 2778-2020, *IEEE Guide for Solar Power Plant Grounding for Personnel Protection*.
3. IEEE Std 81-2012, *IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System*.
4. IEEE Std 367-2012, *IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault*.
5. IEEE Std 665-1995, *IEEE Guide for Generating Station Grounding*.
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Case data

- Grounding study and protection and selectivity study of the plant, prepared by the project's engineers of record (anonymized; values adapted to U.S. practice for illustration).
- Utility short-circuit data and feeder relay settings provided for the interconnection study.

Annex A: Companion Spreadsheet

The spreadsheet *Solstice_Grid_Protection_CTH_Tool.xlsx* reproduces the method of this paper. Yellow cells are inputs; the result and the coordination chart update automatically. It opens with the values of this case. It is a screening and training aid: its results must be verified by the Engineer of Record and do not constitute an engineering study or design.

Sheet	Content
Guide	Purpose, step-by-step use, equations and limitations.
Calculator	Inputs (fault data, person and surface layer, grid figure G, two relays, clearing device), results (K_{TH}, K_{THM}, ratio, PASS/FAIL, $t_{f,max}$, CTH points, full-curve check) and the coordination chart.
IEEE80 Grid	Optional simplified IEEE 80 calculation of G for a rectangular grid in uniform soil.
Curves	Constants of the IEEE C37.112 and IEC 60255-151 inverse-time curves and definite time.
Calc	Chart data and helper calculations (not to be edited).

Results		
Body-current constant k (IEEE 80)	0.116	A·s½
Fault clearing time t_f	**0.741**	s
DC offset time constant T_a = (X/R)/ω	0.0472	s
Decrement factor D_f(t_f)	1.031	-
ıseSurface layer reduction factor C_s	0.756	-
C_s·ρ_s	2,268	Ω·m
Tolerable touch voltage at t_f	593.3	V
Grid figure G	4.737	S (A/V)
Fault current used for timing, I_f × C_p	3,427	A
Maximum grid current I_G = C_p·D_f·S_f·I_f	3,535	A
Expected maximum touch voltage = I_G / G	746.2	V
K_THM — grid capacity = k·(1000+1.5·C_s·ρ_s)·G	**2,419**	A·s½
K_TH — demand = I_G·√t_f	**3,042**	A·s½
K_THM / K_TH (margin)	**0.80**	-
Result	**FAIL**	touch criterion not met
Maximum allowed clearing time for I_f × C_p	**0.451**	s
CTH point BL1: t = (k/0.05)²	5.382	s
CTH point BL1: current	1,306	A
CTH point BL2: t = (k/0.5)²	0.0538	s
CTH point BL2: current	9,808	A
K_THM point on the chart: current at t_f	2,725	A
Full-curve check (relay time vs. grid limit, I ≤ I_f × C_p)		
Relay 1	**OK**	≈ current range where the relay is slower than the grid allows
Relay 2	**2,677 – 3,417 A**	≈ current range where the relay is slower than the grid allows

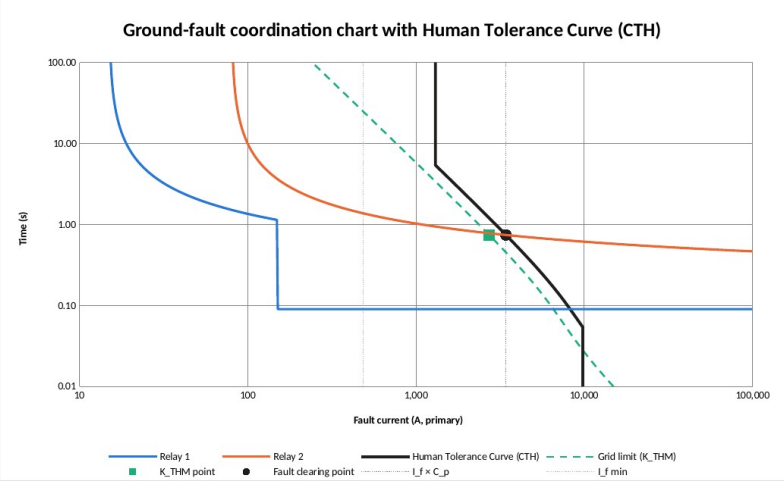


Figure 4. Calculator sheet: results and coordination chart for scenario S3.

Annex B: Study Record Template

The record below summarizes the choices made in this analysis and can be reused for other plants.

Item	This case
Plant / POI	2.5 MWac PV plant · 34.5 kV three-wire feeder (anonymized)
Area analyzed	POI switchgear (metering and protection)
Fault data	I_f = 2,980 A, X/R = 17.8, C_p = 1.15, S_f = 1.0, $I_{f,min}$ = 487 A
Safety parameters	50 kg · ρ = 642 Ω·m · crushed rock 3,000 Ω·m, 4 in (C_s = 0.756)
Grid figure	G = 4.74 S (3,600 A / 760 V, plant-wide model)
Protection	Plant 50N 150 A + 51N IEEE MI; utility 51N IEEE MI 80 A, TD 0.85
K_{THM}	2,419 A·$s^{1/2}$ with rock; 1,079 A·$s^{1/2}$ bare soil
Results	S2 PASS (1.91) · S3 FAIL (0.80); $t_{f,max}$ = 0.45 s
Mitigation adopted (Engineer of Record)	
Engineer of Record (PE) – name, license no., jurisdiction / date	
Reviewed by / date	