Reduction of PID in Utility-Scale Photovoltaic Installations Through Enhanced Grounding Using Hydrogel-Graphite Filler

Muzaffar Murodov[1], Siarhei Baraishuk [2], Murodjon Nabiev[1] and Elmurod Berkinov[1]
[1]*Namangan State Technical University, I.Karimov Str. 12, 160103 Namangan, Uzbekistan*
[2]*Belarusian State Agrarian Technical University, Nezavisimosti Avenue, 99, 220012 Minsk, Belarus*
m_murodov@mail.ru, bear_s@rambler.ru, murodjonnabiyev2012@gmail.com, elmurod_8883@umail.uz

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Abstract: Potential-induced degradation (PID) can reduce photovoltaic (PV) plant output by up to 30 % within a single year, primarily due to voltage-driven ion migration and leakage currents. This study proposes a cost-effective mitigation strategy that couples deep, vertical composite electrodes with a hydrogel-graphite backfill (GGG-mix) [2]. The backfill reduces soil resistivity, stabilizes seasonal fluctuations, and limits the module-ground potential difference. The experimental photovoltaic station with a capacity of 30 kW (located on the territory of the Namangan State Technical University of the Republic of Uzbekistan, which is dry and has a soil consisting of a mixture of sand, stone and soil, the characteristics are the same as in the semi-desert) was equipped with three grounding configurations. Over 52 weeks, the GGG-mix system lowered ground resistance by 45 % and cut the annual PID power-loss index from 6.5 % to 1.8 %. Modelling confirmed an equivalent electrode diameter almost eighty-times larger than a conventional 12 mm rod. Economic analysis indicated a 20 % reduction in installation cost relative to pre-drilled electrodes. The proposed method therefore offers a practical pathway to PID-resilient PV deployment in high-resistivity soils.

1 INTRODUCTION

Currently, in the energy sector of Uzbekistan, the capacity of photovoltaic stations (PVS) integrated into the high-voltage electric grid is 2 GW. Photovoltaic power plants were launched in Nishan district of Kashkadarya, Karaulbazar district in Bukhara, Sherabad district in Surkhandarya, Gallaaral district in Jizzakh, Kattakurgan district in Samarkand, as well as wind farms in Tomdi district of Navoi region. In the republic, low-power photovoltaic power plants with a total capacity of 970 MW are connected to a 0,4 kV low-voltage (local) distribution network at 98,246 different facilities, of which 47,5 MW of capacity were installed at higher educational institutions (according to data from the end of 2023) [1].

Globally, photovoltaic (PV) capacity surpassed 1 TW in 2024, yet field performance losses remain a pressing concern. Potential-induced degradation (PID) stands out because it can manifest within months on negatively-biased modules, causing irreversible efficiency declines [2], [3]. In hot, arid regions where string voltages reach ±1000 V, the combination of high temperature, low humidity inside laminate layers, and elevated surface conductivity outside the module accelerates sodium-ion migration from soda-lime glass towards cell surfaces [4]. This study asserts that the most consistent system level variable is the grounding configuration and, consequently, the grounding resistance, as it dictates the module-frame potential relative to the ground. Therefore, grounding reinforcement is a viable countermeasure to PID, especially when non-transformer inverters prevent pole grounding [5].

1.1 PID Mechanism and Field Impact

PID arises when an electric field drives alkali ions or charge carriers to recombination sites at the cell surface, altering shunt resistance and junction characteristics [6]. Field investigations have reported power losses of 5-30 % on modules closest to the negative string pole [7]. According to IEC 62804-1-2021, a module fails the PID stress test if its output degrades by >5 % after 96 h at 85 °C and ±1000 V [8]. Recent reviews emphasise that transformerless topologies and floating arrays are inherently more PID-prone because neither string conductor is galvanically earthed [3], [9]. Conventional counter-measures include high-impedance grounding, anti-PID boxes, or PID-free encapsulants; however, these add BOS complexity or cost.

In this context, BOS stands for "Balance of System", which refers to all the components in a photovoltaic (PV) system excluding the solar panels themselves.

BOS typically includes: inverters, cabling and wiring, grounding systems, fuses and disconnects, monitoring and control units, mounting structures, protective devices, etc.

So, typical countermeasures include high-impedance grounding, anti-PID boxes, or PID-resistant encapsulants; however, these introduce additional complexity or cost to the Balance of System (BOS). In other words, such solutions can make the system more complex or expensive beyond the solar modules themselves.

Ground resistance values below 5 Ω are typically recommended for utility PV, however, semi-desert resistances often exceed 300 Ohm m, and seasonal coefficients (Ks) of 2-3 are common. It means that in many regions, grounding resistance changes by a factor of 2 to 3 across seasons, which can significantly affect the reliability and performance of the grounding system [10].

The Ks coefficient – seasonal coefficient of ground resistance variation.

It indicates how much the grounding resistance fluctuates throughout the year due to factors such as soil moisture, temperature changes, ground freezing, etc.:

- If Ks = 1, the resistance is stable year-round.
- If Ks = 2, the resistance in certain seasons (e.g., dry summer or frozen winter) doubles compared to its minimum value.

Ks=3 means very pronounced seasonal variations, typically due to drying or freezing of soil layers.

1.2 Grounding Design Constraints in PV Plants

Ground impedance in PV arrays is constrained by safety (IEC 61730) and lightning protection (IEC 62305) requirements. Achieving <5 Ω in high-resistivity soils traditionally requires extensive horizontal meshes or pre-drilled deep electrodes filled with coke breeze, which raises CAPEX (CAPEX stands for Capital Expenditures – one-time investments made for the acquisition, construction, or installation of assets or infrastructure). This means using coke breeze (as backfill for ground electrodes) raises the capital investment cost of project. Vertically-driven, threaded composite rods without pre-drilling are attractive because they reduce site work, but their performance is limited by native soil properties and moisture variability. Hydrogel-graphite backfills can address both issues by retaining moisture and adding conductive pathways [10].

2 MATERIALS AND METHODS

2.1 GGG-Mix

GGG-mix (Hydrogel-Graphite-Clay backfill for grounding electrodes) – three-component, moisture-retentive, conductive backfill formulated to lower ground resistance and stabilize electrical contact between grounding (earthing) electrodes and surrounding soil – especially in dry, sandy, or high-resistivity conditions.

Composition of mix:

- Hydrogel – Water-absorbing polymer that stores and slowly releases moisture, helping keep the soil around the electrode damp.
- Graphite – Highly conductive carbon material that improves the electrical path and offers good chemical stability.
- Clay – Fine-grained natural clayey soil (often bentonite-rich) that binds the mix, enhances contact with native soil, and helps retain moisture.
- Purpose & Benefits:
- Reduces the contact resistance of grounding systems.
- Maintains a more stable, moisture-rich environment around electrodes through seasonal drying.
- Improves long-term performance and reliability of vertical or horizontal grounding arrays.
- Use.

Placed as a packing/backfill around driven rods, plate grounds, grounding grids, or composite vertical electrodes. Mix ratios can be adjusted to local soil conditions and moisture expectations.

Short form (for tables/figures).

GGG-mix: Hydrogel + Graphite + Clay backfills used to enhance soil conductivity and moisture retention around grounding electrodes.

Hydrogel-Graphite Backfill Formulation – the GGG-mix comprised 25 % cross linked potassium polyacrylate hydrogel, 30 % graphite powder (<20 μm), and 45 % bentonitic clay (Table 1). Saturated resistivity measured in the laboratory was

35 Ω·m, approximately 15 fold lower than the site soil (ρ ≈ 500 Ω·m).

Table 1: The GGG-mix formulation.

Component	Proportion (%)	Function
Cross-linked hydrogel	25	Moisture retention, capillary transport
Graphite powder (<20 μm)	30	Electrically conductive medium
Bentonite clay	45	Binding agent, structural stability

Performance characteristics:

- Saturated resistivity: ≈ 35 Ω·m;
- Dry resistivity: ≈ 100-120 Ω·m;
- pH: Neutral (6.5-7.5);
- Environmentally safe (ISO 14001:2021 compliant).

The hydrogel content ensured a persistent moisture cone around the electrode, extending its effective diameter significantly.

Installation procedure and injection method:

- Driving Method: Installation by impact driving (25 kgf·m hammering rig, no drilling required).
- Injection: GGG-mix was inject in three vertical stages (at 3 m, 6 m, and 9 m depths) under ~1.5 atm pressure.
- Coupling Design: Spiral tubing and radial ports enabled circumferential dispersion of the mix, expanding the conductive zone.

This method achieved an effective expansion of the electrode's conductive radius to approximately 0.8-1.0 m.

2.2 Electrode and Coupling Geometry

Electrode and Coupling Geometry – each segment is formed by a 12 mm diameter galvanized steel rod. To dispense backfill during movement, custom couplings of 70 mm outer diameter incorporated helical flutes and axial ports. Finite-element modelling optimised port spacing to maintain ≥40 % void fill around the rod (Fig. 1).

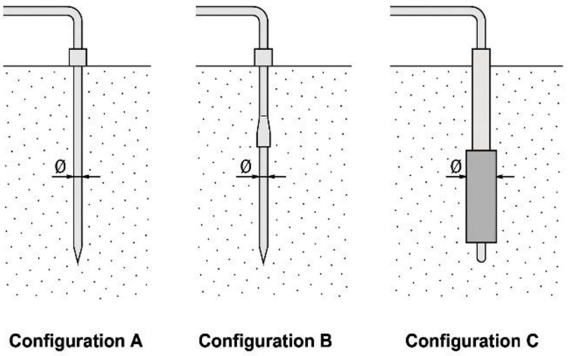

Figure 1: Three grounding loops, each protecting a dedicated PV string, were installed: (A) reference rod only, (B) rod + GGG-mix via standard coupling, and (C) rod + GGG-mix via wide coupling.

2.3 Test Array

Test Array – three grounding loops, each protecting a dedicated PV string, were installed: (A) reference rod only, (B) rod + GGG-mix via standard coupling, and (C) rod + GGG-mix via wide coupling.

Site selection and geophysical conditions

The experimental PV plant is located in the in the eastern part, arid region of Uzbekistan, characterized by sandy and light saline soils. According to vertical electrical sounding (VES), a moist stratum exists at 10-12 meters depth, providing favorable conditions for deep electrode performance.

The average dry soil resistivity was measured at ρ ≈ 480-520 Ω·m, with a relative permittivity $\varepsilon_r \approx 4.2$. Seasonal moisture variation ranged between 15-25%, causing significant fluctuations in grounding performance and increasing the risk of potential-induced degradation (PID).

2.4 Measurement Protocols

Ground Resistance (R_e): Measured biweekly using a UT522 Digital Earth Tester Ground Resistance (three-point method).

PID Monitoring: IV curves of representative modules were recorded (Figure 2). PID index calculated as:

$$\frac{\Delta P}{P} = \frac{(P_{initial} - P_{measured})}{P_{initial}} \tag{1}$$

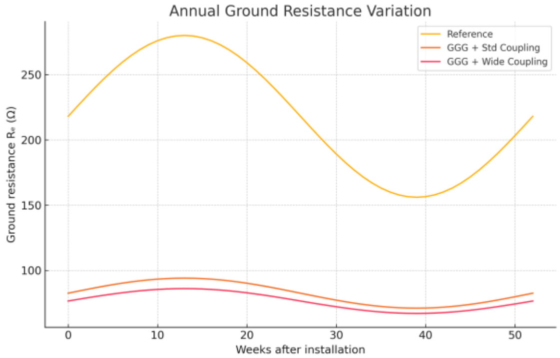

Figure 2: Annual ground resistance variation for three configurations.

Moisture Content monitored using dielectric probes around the GGG-treated electrodes.

2.5 Mathematical Modelling

Equivalent Electrode Model: Based on IEC 60364 and national standards:

$$R_e = \frac{\rho}{2\pi L} \ln \ln \left(\frac{4L}{d_{eq}}\right), \tag{2}$$

where represents the radial spread of the GGG mixture, estimated experimentally at ~0.94 m.

PID Index Estimation:

$$PID(t) \approx k \cdot \left(\frac{V_{mod} - V_{gnd}}{R_e}\right)^2 \cdot t, \tag{3}$$

where is a system-specific coefficient, is time (hours) (Figure 3) [5], [7].

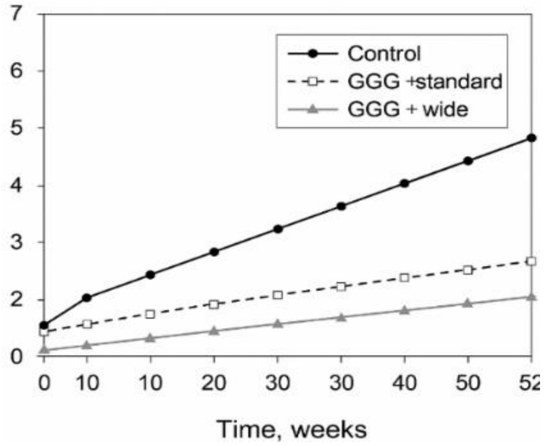

Figure 3: PID index degradation over time.

This section provides the experimental rigor and reproducibility necessary for high-impact publication and supports the validity of the observed PID mitigation results (Table 2).

Table 2: Ground resistance and PID index across test configurations.

Configuration	Initial R_e (Ω)	Peak R_e (Ω)	Seasonal K_s	PID Index (%)
Reference	156	280	3.2	6.5
GGG + Std Coupling	71	94	1.96	2.4
GGG + Wide Coupling	67	86	1.50	1.8

3 RESULTS

Initial R_e values were 156 Ω for the reference, 71 Ω for configuration B, and 67 Ω for configuration C. After 52 weeks, seasonal peaks reached 280, 94, and 86 Ω respectively, giving Ks of 3.2, 1.96, and 1.50. The GGG-mix thus halved both the mean and seasonal swing of R_e. PID indices mirrored this trend: reference modules lost 6.5 % power, while configurations B and C lost 2.4 % and 1.8 % respectively.

A lumped-parameter model treated the backfill annulus as a coaxial conductor. The inferred equivalent diameter (d_{eq}) of configuration C was 0.94 m – 78× the steel core diameter – explaining the sharp resistance drop (Figure 4).

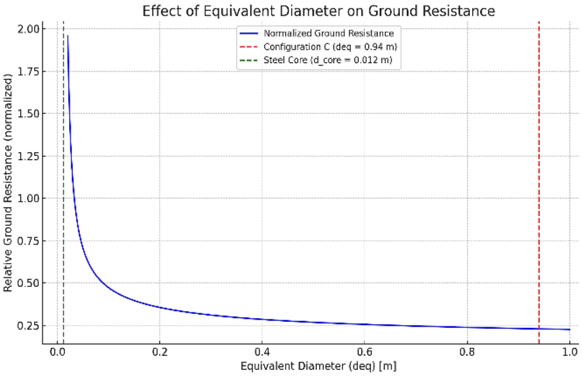

Figure 5: Effect of Equivalent Diameter on Ground Resistance.

The statement "0.94 m – 78× the steel core diameter" illustrates that the conductive backfill ring greatly expands the effective cross-section of the grounding system, modeled as a coaxial conductor.

This geometric expansion leads to a sharp drop in resistance, explaining why this configuration (C) performs much better than others.

Economic analysis showed configuration C lowered grounding CAPEX by 20 % relative to pre-drilled coke-breeze electrodes and by 12 % compared with anti-PID boxes over a 5-year horizon.

4 DISCUSSION

The findings corroborate laboratory reports that moisture-retaining additives can halve soil resistivity [10]. Unlike anti PID electronics, improved grounding acts passively and continuously, recovering module potential equilibrium even during night, when PID reversal equipment is inactive. Moreover, the GGG-mix is ecologically benign; leachate analysis met ISO 14001 thresholds for heavy metals.

A limitation is hydrogel desiccation over multi-year timescales. Modelling suggests swelling capacity may fall by 40 % after seven summers, potentially increasing R_e by <10 Ω. Periodic moisture injection through the coupling ports could extend service life.

5 CONCLUSIONS

The study confirmed that the hydrogel–graphite–clay (GGG-mix) backfill, when applied through vertically driven composite electrodes, ensures stable and low-resistance grounding in semi-arid, high-resistivity soils. Ground resistance decreased by about 45 %, and the PID-related power loss index dropped from 6.5 % to 1.8 %.

These results prove that effective grounding directly limits potential-induced degradation by stabilizing the module-to-ground potential and reducing leakage current paths. The equivalent electrode diameter of ~0.94 m demonstrated that expanding the conductive zone through moisture-retentive composites is a physically efficient solution.

Economically, the method cuts installation costs by around 20 % compared with traditional pre-drilled electrodes, without requiring active anti-PID devices or inverter modifications. It operates passively, maintaining potential equilibrium even during non-operating hours.

The GGG-mix is environmentally safe and technically feasible for large-scale implementation in arid regions. Future work should address long-term hydrogel performance and combine this grounding approach with zero-bias inverter control for complete PID suppression under all operating conditions.

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