

TECHNICAL NOTE

Solar Generators in Weak Grid Environments

Failure Modes, Mitigation Strategies & Grid Scenarios



ISSUE 01 | DECEMBER 2024

PREPARED BY:

Frieder Rabl

frieder.rabl@a2ei.org

Senior Engineer

Access to Energy Institute

Table of Content

Abstract	2
Introduction	3
Technology Outline of Hybrid Inverters	3
Description of Common Failures of Hybrid Inverters in Weak-Grid Environments	5
Potential Mitigation Strategies	6
Grid Monitoring in Abuja	7
Simulation of Grid Scenarios and First Results	10
Outlook	12

Abstract

This technical note examines challenges hybrid solar generators face in weak grid environments, focusing on issues observed in power electronics. The note highlights vulnerabilities arising under unstable grid conditions and suggests initial approaches for addressing these, including design adaptations and protective measures. Based on grid monitoring data from Nigeria, it also details plans for targeted hardware testing to validate system reliability and prevent in-field failures.

Introduction

In recent years, hybrid solar generators have emerged as a valuable solution for energy resilience, combining solar power and grid connectivity to power private households as well as small to medium enterprises (SMEs) with reliable power in regions with weak or inconsistent grid access. Solar Generators provide a stable source of AC power during grid outages and eliminate the need for fossil-fuel-based generators. Many off-grid solar companies, initially focused on rural households, are now expanding their services in the space of hybrid solar generators. However, while leveraging grid power in hybrid solar setups can reduce the required battery capacity and enhance supply stability, it also exposes the system's electronics to the risks of grid instability. Such vulnerabilities could potentially impact customer trust in the products, safety, and the viability of solar-powered solutions as a dependable alternative to conventional power sources.

This technical note aims to present a selection of common challenges hybrid solar generators face in weak grid environments, focusing on issues observed in power electronics. By outlining typical failures and sharing early findings from grid monitoring, this note highlights the specific vulnerabilities that arise under unstable grid conditions and suggests initial approaches for addressing these. Together with following technical notes the goal is to support ongoing improvements in product quality across the market by documenting viable solutions and best practices that can guide design adaptations and protective measures for solar generators. Additionally, this note discusses plans for targeted hardware testing informed by these observations, aiming to validate system reliability and prevent in-field failures,

ensuring a dependable and safer user experience.

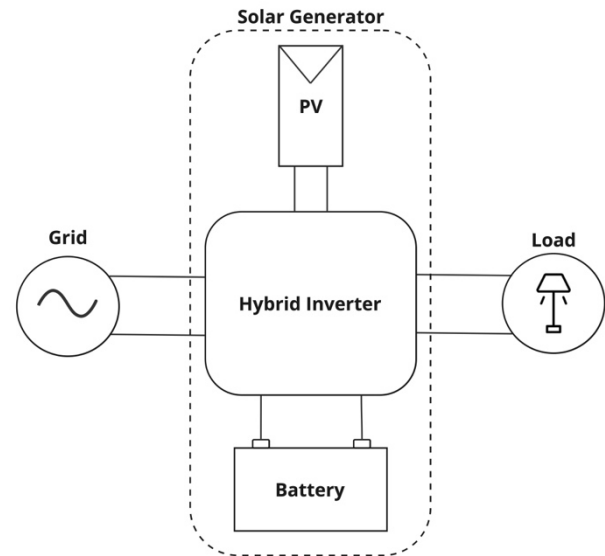


Figure 1- Solar generator

Technology outline of hybrid inverters

Hybrid inverters are central to the operation of solar generators, enabling energy management across different power sources: solar panels, battery storage, and the electrical grid. These inverters combine several main components (Figure 2):

- **Inverter / Charger:** This bidirectional component enables energy transfer from the grid to the battery (charger mode) or from the battery to the inverter output (inverter mode).
- **PV Charge Controller:** Manages the power coming from the solar panels to either directly charge the battery or to provide an additional input to the inverter / charger.
- **Relay / Fuses / Protection:** Essential for safety, these components protect the system from electrical faults.
- **Control Unit / UI / Communication:** The control unit manages system operations,

while the user interface and communication systems allow monitoring and adjustments.

In addition to these core components, a hybrid system also includes **PV modules**, **battery storage** and **external protection & safety components**.

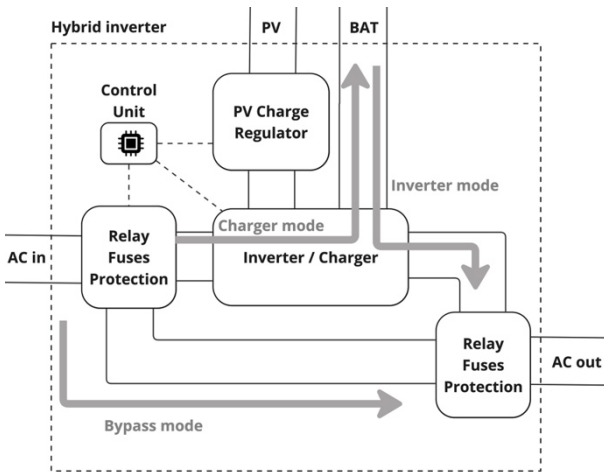


Figure 2 - hybrid inverter components and operation modes with power flow

Inverter / Charger Topologies

The design of the inverter/charger has a direct impact on system efficiency, robustness, and cost. There are two main types of inverter topologies in hybrid systems:

1. **Low-Frequency Inverter** (Figure 3): This type uses a low-frequency transformer to connect the DC and AC sides often with a single h-bridge for rectification. Low frequency transformers can hold more energy, meaning they can handle surge power well. They also have fewer switching components. Therefore they are often associated with durability and resilience. However, low-frequency inverters tend to be heavier, less efficient, and more expensive due to the materials used for the big transformer.

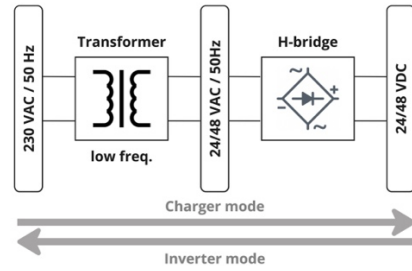


Figure 3 - Low frequency topology

2. **High-Frequency Inverter** (Figure 4): High-frequency inverters use advanced switching components and operate at higher frequencies. Thus, reducing transformer size and enabling a lighter and more compact design. They also incorporate a high-frequency transformer to maintain safety through isolation. While these inverters are generally more efficient and cost-effective, their complex design can make them less robust than low-frequency types.

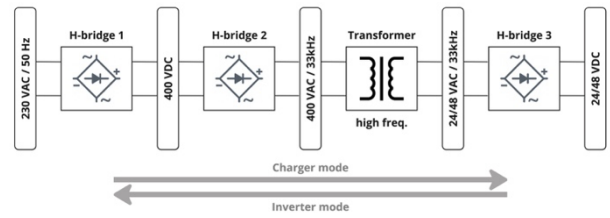


Figure 4 - High frequency topology with exemplary voltage and frequency levels

Regardless of the chosen topology, several fundamental factors significantly impact the reliability and robustness of hybrid inverters. Key considerations include:

- **Firmware and Hardware Integration:** The interplay between firmware and hardware within the inverter is crucial for seamless responsiveness under varying conditions.
- **Power Component Dimensioning:** Proper sizing of power-carrying components enhances durability.

- **Protection Circuitry Design:** Robust design of protective circuits safeguards against electrical faults, overvoltages and overcurrents.

These elements, alongside installation practices, are critical in terms of stability, longevity, and suitability for use in challenging grid environments.

Description of common failures of hybrid inverters in weak-grid environments

Hybrid inverters operating in weak grid environments face unique challenges that can lead to failures in critical components. These failures often result from grid instability, which exposes sensitive electronics to voltage fluctuations, transients and frequent changes in the operation mode. Below, we discuss three commonly observed failure modes and potential mitigation strategies.

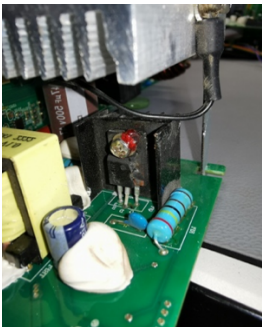


Figure 5 – burned Mosfet of the flyback converter



Figure 6 - Burned resistor and traces

1. AC Auxiliary Supply Circuitry

The AC supply in hybrid inverters serves not only to deliver power to the user or charge the battery but also in some cases to provide auxiliary power to critical segments such as the PV charge controller as well as communication, control and sensing

circuitry. This connection exposes sensitive electronics to grid instabilities.

A common failure observed in our field-data involves a **flyback converter**, which powers the PV charge controller. Despite the presence of input filters and protection circuitry, several components in the converter (MOSFET, resistor & diode) have been found damaged, leading to complete PV charge controller failure. These failures could be attributed to overvoltages that pass the filter and protection systems, highlighting the need for improved design to handle grid fluctuations.

2. AC Input Protection and Relay Circuitry

Certain circuits, such as input protection systems and relays, are inherently exposed to grid conditions. Input protection circuitry employs components like MOVs (Metal Oxide Varistors) to limit overvoltages, while relays manage the connection and disconnection of the inverter to the grid based on grid stability.

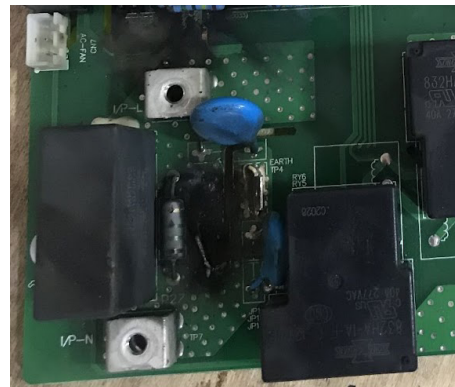


Figure 7 - Burned varistor at inverters AC input

Field data has shown failures in both MOVs and input relays. While single overvoltage events may damage MOVs, frequent voltage fluctuations and switching cycles in unstable grids contribute to excessive wear, particularly on relays. These failures are critical, as they potentially compromise the inverter's protection mechanisms and may

lead to cascading faults in other components.

3. H-Bridge Power Switching Components

To convert energy between DC and AC, inverters utilize transformers and H-bridges comprising electronic switches like MOSFETs and IGBTs. These components carry high power and must be robustly dimensioned to ensure durability.

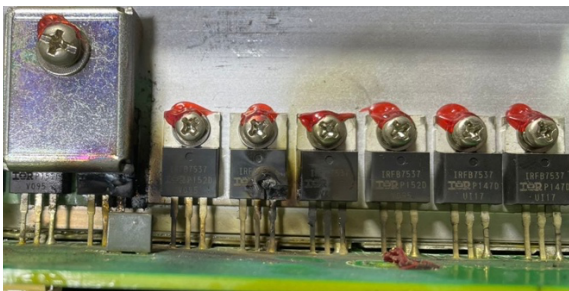


Figure 8 - Burned Mosfet on powerboard

Failures in MOSFETs, IGBTs, and their associated control circuits, such as gate drivers and snubber capacitors, are common in weak grid environments. These failures can be triggered by overvoltages, high current spikes, or unfavorable switching states. The seamless operation of high-frequency switching power electronics depends on precise coordination between hardware, control mechanisms, and grid condition, making them particularly vulnerable to grid-induced disruptions.

Potential Mitigation Strategies

Addressing these failures might require tailored solutions depending on the operating environment and location specific challenges:

1. **Disconnect from the Grid:** In cases where grid stability is highly unreliable, fully disconnecting from the grid can be

the most effective solution. This approach requires careful planning. Without grid connection, PV size, battery capacity and load profiles must be carefully matched to deliver reliable power supply. Use cases with predominantly daytime usage can be suitable.

2. **Adjust Switching Patterns:** To mitigate harmful effects during grid reconnection, inverters can delay switching functions until the grid stabilizes fully. This can help reduce stress on the system. Badly timed switching could also cause failures regardless of the grid condition. Adjusting switching times can be safer, however potentially compromising UPS functionality.
3. **Improve External Protection:** Adding external protection devices, such as Surge Protection Devices (SPDs), spark gaps, or Automatic Voltage Regulators (AVRs), tailored to the specific installation site, can shield inverters from harmful grid conditions. This approach provides flexibility and can be customized for the installation.
4. **Enhance Internal Protection:** Improving the internal protection mechanisms of hybrid inverters can provide a cost-effective way to safeguard sensitive components from grid instabilities. This includes integrating additional SPD's within the inverter, placed strategically after the input filter but before critical electronics. These internal protections can be designed and sized to meet specific operational environments, offering a tailored solution during the manufacturing process.

Additionally, using **high-quality components** with higher withstand voltage ratings can significantly improve the inverter's resilience to overvoltages. While this approach enhances durability

and protection, it comes with increased production costs, requiring careful consideration of the trade-offs between durability and affordability.

5. **Implement Proper Earthing:** In regions like Nigeria, where earthing is often absent, introducing proper grounding practices can significantly enhance the durability of solar installations and other equipment. Distributors could provide this as an added service, along with customer education on its benefits for safety and longevity.

By addressing these common failures and implementing appropriate protective strategies, hybrid inverters can achieve higher reliability and robustness, ensuring their effectiveness in weak grid environments.

Grid monitoring in Abuja

As highlighted in the previous section, identifying the exact causes of inverter failures can be challenging. While the mitigation strategies discussed earlier play a critical role in strengthening solar generators, there are still cases where the root cause of failures remains unclear. Insights from affected units in the field can be informative, but initial assumptions often lead to oversimplifications. For instance, some error patterns may appear to be caused by high voltage levels but ultimately prove unrelated to voltage magnitude.

To better understand the operational environment of solar generators, it is essential to monitor and analyze grid behavior. Over the past year, we have deployed three Powerwatch voltage meters from nLine to collect data on grid conditions in Abuja. These meters measure voltage and frequency using two-minute averages and capture transients at a 5kHz resolution

during outages and restorations of the power grid. The devices were installed in diverse settings, including an office building, a private household, and a typical market.

Although the limited number of meters restricts the generalizability of the findings, certain observations provide valuable insights into potential contributors to inverter failures. Key observations include:

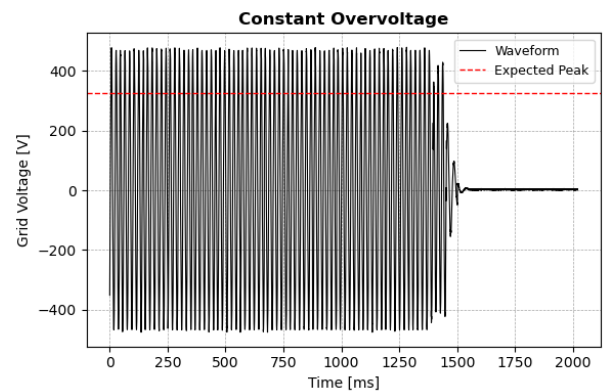


Figure 9 - Constant overvoltage in the grid

Constant Overvoltages: Transient recordings as well as 2-minute average readings revealed peak voltages as high as **480V** (Figure 9). These voltage levels could damage sensitive components if not properly mitigated.

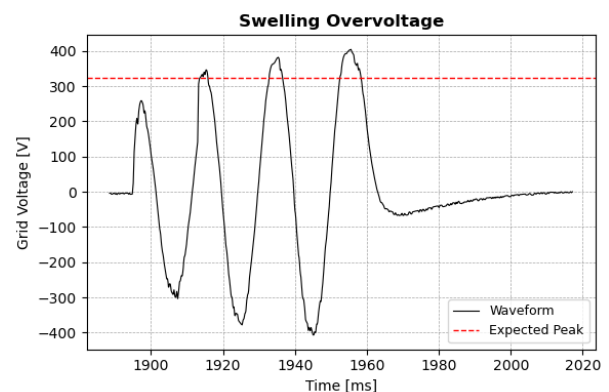


Figure 10 - Swelling Overvoltage

Swelling Overvoltage: Gradual voltage increases, or "swelling," were observed in the grid. These events can lead to sustained

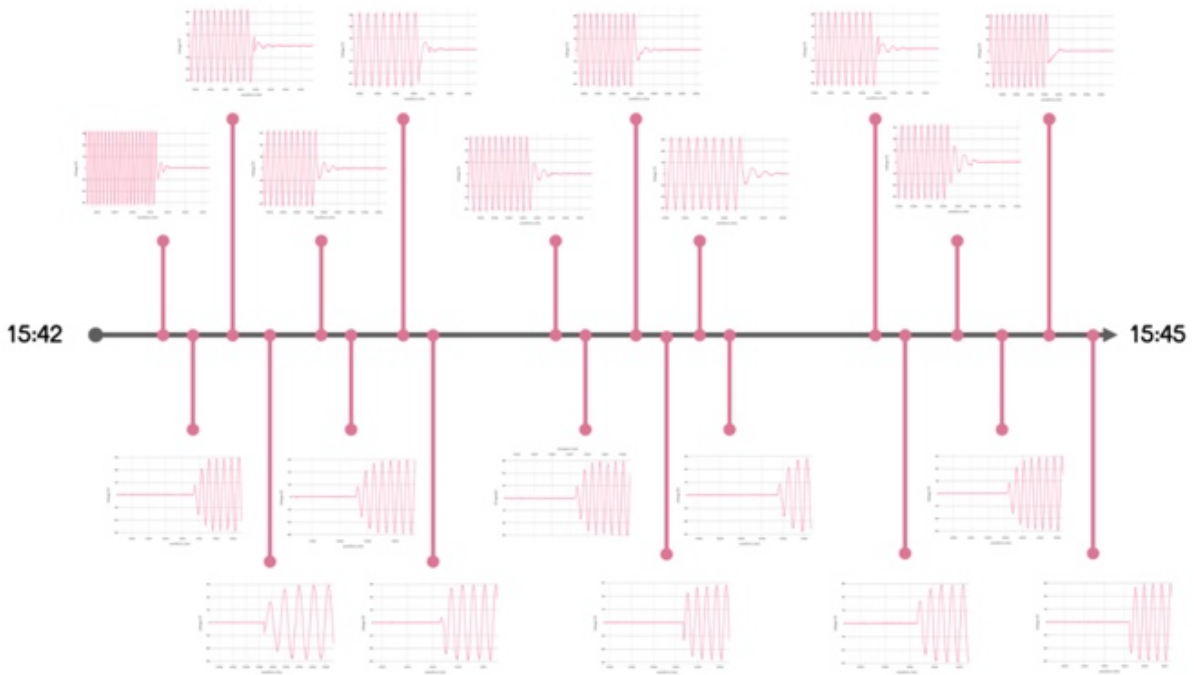


Figure 11 - Sequence of 20 outage & restore events over a period of 3 minutes

overvoltage, posing risks to solar generators. **(Error! Reference source not found.)**

Repeating Outages and Restorations: Frequent sequences of outages followed by restorations were recorded, sometimes repeating over 20 times within minutes. Although individual transients or voltage levels in these sequences appeared unremarkable, the overall instability could disrupt sensitive timing mechanisms in control circuits. (Figure 11)

Outage Sequences with Varying Voltage Levels: Some outages and restorations exhibited intermediate voltage levels, such as 20V, 50V, or 150V, creating ambiguous states for inverter control units. **(Error! Reference source not found.)** Although these voltage levels are not inherently damaging, they may lead to erratic behavior in control systems. 2-Minute-Average values

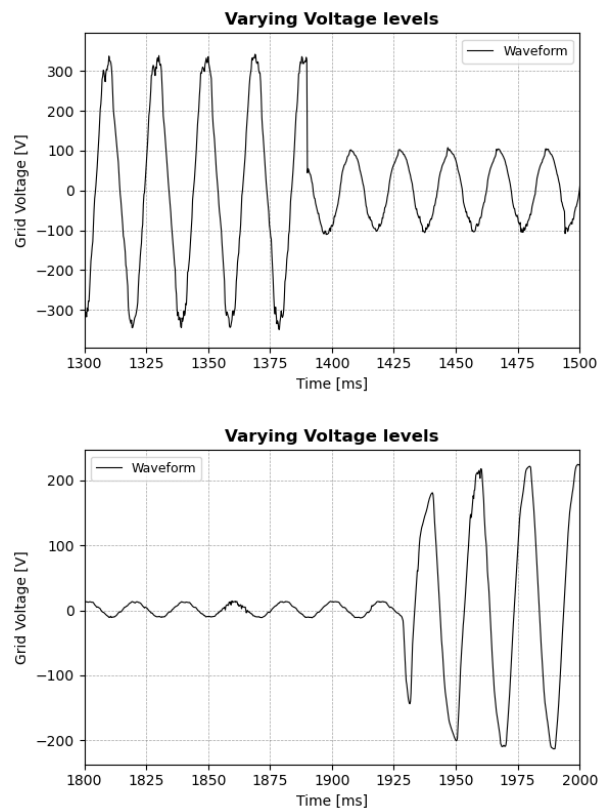


Figure 12 - Varying voltage levels in the grid

imply, that these intermediate voltage levels also appear in a continuous manner.

Incomplete Restores and Outages: Instances of incomplete grid transitions, where the grid briefly restored or disconnected for just a few cycles, were observed. These rapid shifts add complexity to the inverter's ability to respond reliably.

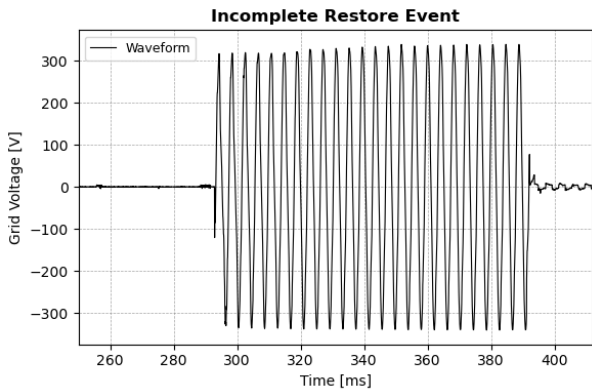


Figure 13 - Incomplete Restore Event

High Frequency Variations: At the market location, grid frequencies reached alarming levels (Figure 15, hitting up to **100Hz** while voltages remained around **200Vrms**). Such deviations could severely impact the operation of inverters designed for standard frequencies.

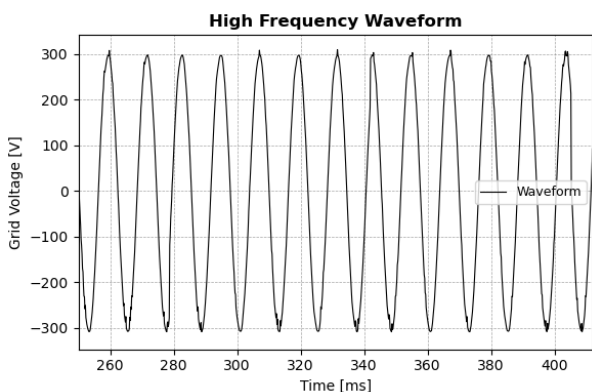


Figure 15 - >80Hz frequency at 212 Vrms

Grid Irregularities: Outage and restoration events frequently exhibited irregularities

such as voltage jumps, ringing, and other artifacts, further complicating the operational stability of connected inverters.

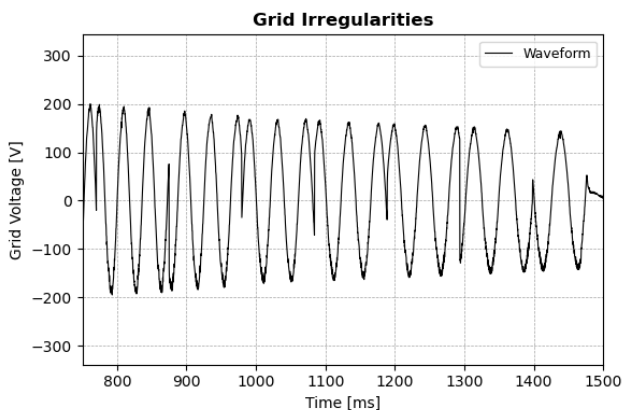
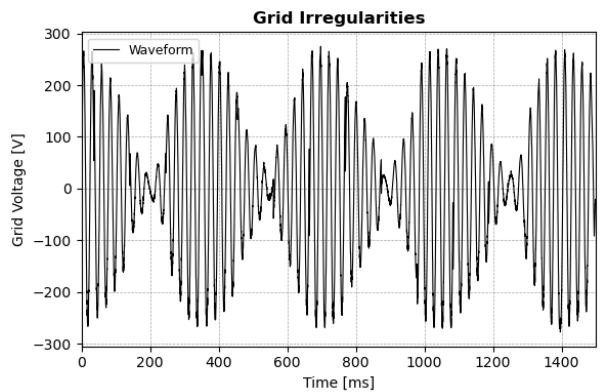
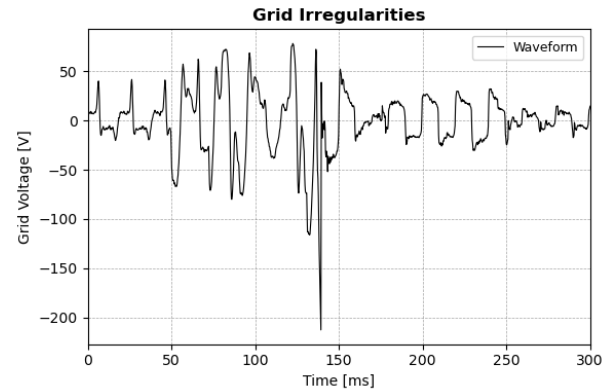


Figure 14 - Grid Irregularities

Harmonics: The presence and intensity of harmonics in the grid can vary greatly depending on the location. While our data predominantly indicates harmonic levels within IEC limits, it is reasonable to assume that other locations may experience

significantly higher harmonic distortion, presenting additional challenges for solar generators.

This analysis does not aim to provide a comprehensive catalog of all grid instabilities but rather a starting point for understanding the challenges hybrid solar generators face. Variations in voltage levels, sequence patterns, and other characteristics are likely, depending on location and grid dynamics.

Some of these scenarios may not negatively impact IEC-certified inverters, but their interaction with specific measurement and control techniques as well as operational behaviors requires further examination. Understanding what to expect from the grid is only the first step. The next step is to evaluate how existing technologies respond to these realities and identify areas for improvement.

Simulation of grid scenarios and first results

Building on insights from grid monitoring in Nigeria, we now have the foundation to replicate local grid conditions in a controlled lab environment. This approach enables us to test and improve the robustness and reliability of solar generators under scenarios that mimic real-world challenges. While this does not replace the need for field trials, it offers a significant advantage by identifying design weaknesses early in the development process, reducing failure rates and development costs.

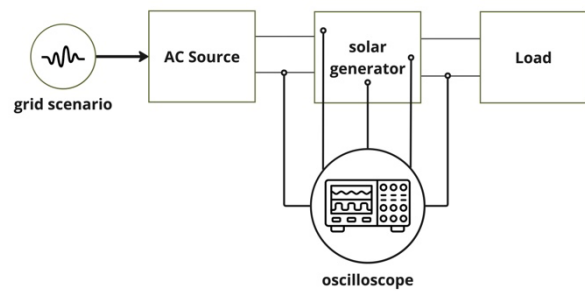


Figure 16 - grid simulation test setup

At **A2EI**, we have established lab facilities specifically designed to simulate "Nigerian conditions." Central to this setup is a **programmable AC power source (Chroma 6500)**, which allows precise control of voltage and frequency sequences, including harmonics. Transients can also be introduced through imported CSV files, enabling the recreation of scenarios observed during grid monitoring. Although the AC power source has a voltage limit of 300Vrms, connecting an upstream transformer allows us to simulate the higher voltages recorded in the field.

To better understand potential failure modes, **oscilloscope probes** are placed at critical points in the circuit, such as the AC input, behind the input protection circuit, and at the H-bridge. This enables detailed analysis of the inverter's behavior under simulated conditions.

Initial Test Results

Our first tests of hybrid inverters under Nigerian grid scenarios have been both revealing and, in some cases, destructive. For example, the failure of the flyback converter powering the PV charge controller (1. AC Auxiliary Supply Circuitry) was initially believed to be caused by high AC input voltage. However, lab simulations demonstrated that a specific sequence of

outages and restorations — without the presence of high voltages — triggered the failure. This finding underscores the importance of reproducing real-world scenarios to uncover the true root causes of failures.

Misinterpreting failure modes, such as attributing them to high voltage when the actual cause lies elsewhere, can lead to unnecessary and costly redesigns. These redesigns may not only increase development expenses but also raise the final product price without effectively addressing the underlying issue.

By simulating **Nigerian grid conditions** in the lab, we can identify more targeted and cost-effective solutions. For the described failure, adjustments in control mechanisms may offer a viable resolution without the need of costly hardware changes. This approach accelerates the development process, reduces unnecessary costs, and ensures that design changes genuinely enhance product reliability and durability.

Outlook

This technical note serves as an introduction to our initiative of "bringing Nigeria to the lab," aimed at supporting the sector in improving product quality for customers while reducing development costs for manufacturers. By replicating local grid conditions and analyzing their impact on solar generators, we hope to contribute to the design of reliable and robust hybrid inverters for weak grid environments.

At **A2EI**, we plan to continue publishing technical notes that delve deeper into individual scenarios, exploring specific failure modes and mitigation strategies in greater detail. Additionally, we aim to spotlight challenges that extend beyond grid instabilities, broadening the scope of this initiative.

We invite the sector to actively contribute by sharing their areas of interest and pressing challenges faced in the field. Collaborative efforts can help shape future investigations and ensure the outcomes are relevant and impactful.

To enhance the current "bringing Nigeria to the lab" initiative, the following ideas are proposed:

- **Expand Monitoring Across Diverse Locations:**
The current monitoring data, while valuable, has limitations and does not fully capture the complexities of the Nigerian grid. A collaborative effort to deploy monitoring devices in a wider range of locations would generate a more comprehensive dataset, greatly improving the insights and applicability of the project.
- **Automate Testing and Analysis:**
The current test setup, while effective, is still in its early stages. Automation of

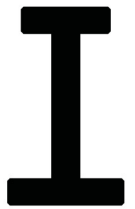
scenario implementation, product testing, and result analysis will accelerate the process, allowing for faster validation of products and more detailed evaluations of their electrical behavior.

- **Comprehensive Product Information:**
While the existing setup can identify root causes of failures, having more detailed information about the product under testing — such as control techniques, firmware workflows, and switching logic — would enhance the ability to reproduce and analyze failures. For instance, understanding the timing requirements for outage and restoration sequences specific to a product can refine testing and lead to more precise conclusions.

We encourage feedback, input, and proposals from industry stakeholders. If you have questions, suggestions, or would like to collaborate, please reach out to our team via SolarGenerator@a2ei.org. Together, we can drive meaningful progress.

A2E

ACCESS TO ENERGY INSTITUTE



OUR WORK IS MADE POSSIBLE BY THE SUPPORT OF OUR FUNDERS:

IKEA Foundation




ZE-Gen.

IN COOPERATION WITH:



THANK-YOU FOR THE SUPPORT:



ACCESS TO ENERGY INSTITUTE

Berlin, Germany | Kampala, Uganda | Abuja, Nigeria

