IJO -INTERNATIONAL JOURNAL OF MECHANICAL AND CIVIL ENGINEERING

(ISSN: 2992-2461) Ifeyinwa Faith Ogbodo2*

https://ijojournals.com/ Volume 08 || Issue 09 || September, 2025 ||

ANALYSIS OF AC VOLTAGE PROTECTION FOR SOLAR-BASED UNIVERSITY FACILITIES: INVESTIGATING VOLTAGE PROTECTION DEVICES AND THEIR ROLES IN STABILIZING AC SUPPLY FOR SENSITIVE EQUIPMENTS

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Abstract: The integration of solar energy systems in university facilities presents both opportunities and challenges, particularly in maintaining a stable alternating current (AC) supply for sensitive laboratory and IT equipment. This project, titled "Analysis of AC Voltage Protection for Solar-Based University Facilities: Investigating Voltage Protection Devices and Their Roles in Stabilizing AC Supply for Sensitive Equipment," aims at assessing the effectiveness of various voltage protection devices in ensuring power quality and system reliability in solar-powered academic environments.With the intermittent nature of solar energy and the possible voltage inconsistencies introduced by photovoltaic systems, safeguarding sensitive electronic infrastructure becomes critical. This study investigates key voltage protection devices, including surge protectors, voltage regulators, automatic voltage stabilizers, and uninterruptible power supplies (UPS). The project evaluates each device based on performance indicators such as response time, voltage regulation accuracy, and ability to mitigate overvoltage, undervoltage, and transients. Through simulation models, field measurements, and comparative analysis, the research identifies optimal protection strategies tailored to hybrid energy systems within university campuses. The outcome of the study shows that integrating voltage protection devices such as stabilizers, surge protection devices, UPS systems, isolation transformers, and dynamic voltage restorers significantly improves the stability of AC supply in solar-based university facilities. These devices safeguard sensitive equipment, reduce the risks of damage from voltage fluctuations, and enhance the overall reliability of solar energy system. The outcomes provide recommendations for enhancing the reliability and longevity of sensitive equipment, ensuring continuous academic and research operations even under fluctuating power conditions.

Key Words: Solar-Based University facility, Uninterrupted Power Supply UPS, AC Voltage Protection, Stabilizing AC Voltage.

Introduction: The increasing global demand for sustainable and environmentally friendly energy sources has led to a significant rise in the adoption of solar power systems, particularly in institutional settings such as universities. Solar energy offers numerous benefits, including cost savings, energy independence, and reduced carbon emissions. As universities strive to become greener and more energy-efficient, many have integrated solar photovoltaic (PV) systems into their power infrastructure Liubčuk et al. (2023). However, while solar-based systems contribute to sustainability, they also introduce certain technical challengesmost notably, voltage instability on the AC supply side.

University facilities often house a wide range of sensitive electrical and electronic equipment, including laboratory instruments, computer systems, servers, and communication devices. These devices require a stable and clean AC power supply for optimal performance and longevity. However, solar systems are inherently variable due to fluctuations in solar irradiance, weather conditions, and load demands. These fluctuations can lead to voltage sags, swells, spikes, and transients, which can compromise the performance of sensitive equipment and, in some cases, result in permanent damageEke, R., &Senturk, A. (2012).

To mitigate such risks, voltage protection devices are employed to stabilize and regulate the AC voltage supplied to critical loads. These devices include surge protectors, voltage regulators, automatic voltage stabilizers, uninterruptible power supplies (UPS), and transient voltage

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suppressors Narang et al. (NREL, 2021). The selection, installation, and performance of these devices are critical to maintaining power quality and ensuring the reliability of power systems in solar-powered university environments.

This study focuses on analyzing various AC voltage protection strategies used in solar-based university facilities. It aims to investigate how different voltage protection devices operate, their effectiveness in stabilizing power supply, and their roles in protecting sensitive equipment from voltage-related disturbancesGupta, S., &Khare, A. (2017). Understanding these dynamics is essential for enhancing power reliability and supporting the long-term sustainability of solar energy adoption in educational institutions.

Research Problem: The integration of solar photovoltaic (PV) systems into university power infrastructure has become increasingly common as institutions strive to reduce operational costs and carbon footprints. However, the variability and intermittency of solar power generation pose significant challenges to maintaining a stable and reliable AC voltage supply, particularly when the system is connected to critical loads and sensitive equipment.

In solar-based power systems, fluctuations in solar irradiance due to cloud cover, shading, and time-of-day variations can cause irregularities in power output Lulbadda, K. T., &Hemapala, U. (2022). These irregularities can lead to voltage instability in the AC supply, manifesting as voltage sags, swells, transients, or harmonic distortions. Such voltage disturbances are particularly harmful in university settings, where sensitive electronic devicessuch as laboratory instruments, servers, communication systems, and advanced computing equipmentare in constant use and highly susceptible to power quality issues.

Despite the availability of voltage protection devices designed to safeguard against these instabilities, many university facilities either lack adequate protection or utilize inappropriate or outdated devices that fail to address specific voltage anomalies Okoro, O. I., &Madueme, T. C. (2006). This situation leads to frequent equipment malfunctions, reduced lifespan of electronics, data loss, and interruptions in academic and research activities.

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There is therefore a pressing need to analyze and evaluate the effectiveness of voltage protection devices in solar-based university facilities. A comprehensive understanding of how these devices function, their suitability for various load types, and their ability to stabilize the AC supply is essential. Without such analysis, universities risk continued exposure to power quality problems that undermine the benefits of solar power adoption.

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This research seeks to address the gap by investigating the types, functions, and performance of AC voltage protection devices used in solar-powered university environments, with the goal of recommending effective solutions for enhancing power quality and protecting sensitive electrical infrastructure.

Methodology: Here the methodology and analytical approach used to evaluate AC voltage protection in solar-powered university facilities. It discusses various voltage protection devices, their functions, and how they help in maintaining voltage stability to protect sensitive equipment. Emphasis is placed on ensuring reliable energy supply and safeguarding critical infrastructure against voltage fluctuations. In solar-based university facilities, the integration of photovoltaic (PV) systems into the existing power infrastructure necessitates robust AC voltage protection mechanisms. Sensitive equipment used in laboratories, data centers, and communication hubs can be adversely affected by voltage fluctuations.

System Overview and Site Selection: The research focuses on analyzing AC voltage protection in solar-powered university facilities to ensure a stable power supply for sensitive electrical and electronic equipment. With the increasing adoption of renewable energy sources like solar photovoltaics (PV) in institutional settings, it is essential to address the reliability and quality of the power delivered, especially considering the variability and intermittency of solar power generation.

In many hybrid power systems deployed across university campuses, solar PV systems are integrated with the main utility grid through inverters and sometimes battery storage. These setups are prone to AC voltage fluctuations due to inconsistent solar irradiance, sudden changes in load demand, and grid-side disturbances. These fluctuations can cause malfunction, degradation, or damage to precision laboratory equipment, computer systems, communication tools, and other sensitive loads.

This research seeks to identify suitable voltage protection devices that can be integrated into such systems to regulate and stabilize the AC voltage output, ensuring uninterrupted and safe operation of critical equipment.

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To conduct a relevant and practical analysis, the study requires selecting appropriate university facilities where solar energy systems are already deployed and where voltage stability is a critical concern. The site selection is based on the following criteria:

i. Availability of Solar PV Systems: The facility must operate a functional solar power system, either standalone or grid-connected.
ii. Presence of Sensitive Equipment: Preference is given to buildings such as laboratories, server rooms, research centers, or administrative blocks with equipment that is vulnerable to voltage fluctuations.
iii. Access to Technical Data: Sites where historical voltage data and energy usage logs are accessible through smart meters or monitoring systems.
iv. Support from Facility Management: Cooperation from the university's technical or electrical maintenance staff for site inspection, data collection, and system understanding.
v. Representative Infrastructure: The site should reflect common challenges faced in typical campus solar installations, making the findings applicable across other similar settings.

A preliminary survey is conducted across various departments and facilities within the university to identify potential candidates. Based on the abovecriteria, one or more representative sites are selected for in-depth study, data collection, and analysis of voltage protection strategies.

Data Collection and Monitoring: The primary objective of data collection and monitoring in this project is to gather relevant electrical parameters and operational data that reflect the voltage stability challenges within solar-powered university facilities. This data serves as the foundation for evaluating the performance of voltage protection devices and understanding the behavior of the AC power supply under various operating conditions.A combination of field measurements, system logs, and interviews is used to collect both quantitative and qualitative data. The following steps outline the process:

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1. Site Inspection and System Audit

- Physical inspection of the solar PV installation, inverter setup, and AC distribution panels.
- Documentation of system configuration, rated capacities, inverter models, and existing protection mechanisms.

2. Monitoring Equipment Setup

i. Installation of power quality analyzers, voltage loggers or smart meters at key points in the system, such as:

- Inverter AC output
- Main distribution board (MDB)
- Equipment input terminals (e.g., lab instruments, servers)

ii. These instruments are set to monitor parameters such as:

- AC voltage levels (RMS)
- Frequency variations
- Voltage sags, swells, and transients
- Load current profiles
- Power interruptions or spikes

3. Data Logging Duration

- Continuous monitoring is conducted over a suitable period (e.g., 2–4 weeks) to capture data during different load cycles and weather conditions, especially when solar output fluctuates (cloud cover, peak sun hours, etc.).

4. Historical Data Retrieval

- Collection of historical data from existing Building Energy Management Systems (BEMS) or inverter monitoring platforms, if available.
- Review of past incident reports, equipment failures, and maintenance logs related to power quality issues.

5. Stakeholder Interviews

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- Interviews or questionnaires administered to facility engineers, lab technicians, and energy managers to obtain insights on:
- Past voltage-related failures or equipment malfunctions
- Frequency and impact of power disturbances
- Current voltage protection strategies in place

Table 1: Data Types Collected

Data type	**Purpose**
Voltage (min, max, average)	To assess voltage stability and identify fluctuation levels
Frequency	To detect any grid-related anomalies
Voltage sag/swell duration	To identify transient events and their duration
Load demand profiles	To correlate load spikes with voltage variations
Fault or trip events	To detect equipment disconnection due to voltage issues
Ambient and solar irradiance	To compare solar output variation with voltage behavior

Data Analysis Preparation

Once collected, the data is compiled and processed for analysis. Time-series plots, statistical summaries, and event logs are generated to visualize and quantify voltage anomalies. This analysis informs the selection and evaluation of suitable voltage protection devices in the next phases of the study.

Table 2: Comparison Based on Key Parameters

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Device Type	Voltage Regulation	Response Time	Protection Features	Integration with Solar	Cost	suitability
AVR	Good	Fast	Over/under voltage correction	Moderate	Moderate	Office and lab equipment
UPS	Excellent	Instantaneous	Voltage regulation, surge, backup power	High	High	Critical IT and research equipment
SPD	None	Instantaneous	Surge and lightning protection	Excellent	Low	Supplemental protection for all systems
Voltage Stabilizer	Good	moderate	Steady output voltage	Moderate	Moderate	Classroom and general load protection
Power Line Conditioner	Excellent	fast	Full power conditioning, noise filtering	Limited	High	High-precision lab and medical equipment
Smart Inverter	Good	fast	Built-in voltage & surge protection	Excellent	High	System-wide solar power protection

From Table 2, the following are the research findings:

i. UPS systems are highly effective for critical and sensitive equipment, offering both protection and backup, but their high cost and limited power capacity make them impractical for large systems.

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ii. SPDs are essential for surge protection, especially in areas prone to lightning or switching transients, but they do not regulate voltage.

iii. AVRs and voltage stabilizers are cost-effective for regulating voltage in non-critical environments.

iv. Smart inverters are ideal for solar-based systems, offering both energy conversion and built-in voltage protection, simplifying installation and integration.

v. Power line conditioners provide the most comprehensive protection, including noise filtering, but are best suited for specialized environments due to high costs.

Simulation and Performance Testing

The objective of simulation and performance testing is to evaluate how well different voltage protection devices perform under various conditions, specifically within the context of a solar-powered university facility. By simulating real-world scenarios, such as voltage sags, surges, transients, and other power quality issues, this phase helps validate the effectiveness and reliability of the selected protection devices.

Result and Discussion:

Case Study- Application in a University Facility

To validate the design and performance of the solar-based AC voltage protection system, a case study was conducted in a university facility utilizing solar energy as a major power source. The facility selected includes IPE department, IPE laboratories, IPE workshop, science laboratories, ICT centers.

4.6.1 Facility Overview

- Location: IPE department, Nnamdi Azikiwe university, Awka.
- System Capacity: 420W*10pcs= 4.2Kw solar PV array with battery backup 240w*4pcs= 960Kw and grid support.
- Key Loads: Servers, laboratory instruments, computers, projectors and air conditioning.

4.6.2 Implementation Details

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- Voltage Protection Devices Installed:
- Surge Protection Devices (SPDs) at inverter and distribution panels.
- Automatic Voltage Regulators (AVRs) for lab and ICT rooms.
- Uninterruptible Power Supply (UPS) for data servers and routers.
- Monitoring Tools Used: Digital voltage loggers and inverter monitoring software.

Table 3: After installing the voltage protection system, the following improvements were observed:

Performance Area	Before Protection	After Protection
Voltage fluctuations	Frequent (±15% from nominal)	Rare (within ±5% range)
Equipment downtime	Regularshutdowns during surges	No shutdowns reported
Maintenance frequency	High due to power-related faults	Reduced significantly
User complaints	Frequent(dataloss, reboots)	Minimal

Results

The following are the results from our data analysis:

The result of this step is a prioritized list of sensitive equipment that is most susceptible to voltage instability. This list serves as a reference for:

1. Locating monitoring points for data collection.
2. Evaluating protection needs for each equipment type.
3. Selecting suitable voltage protection devices to be installed at critical points.

This step ensures that the proposed protection system directly addresses the needs of the most affected equipment, thereby maximizing effectiveness and cost-efficiency.

By establishing a clear set of evaluation criteria, the project ensures a consistent, unbiased, and technically sound comparison of different voltage protection solutions. These criteria form the basis for selecting the most suitable devices to enhance power stability and equipment protection within the university's solar-based electrical infrastructure.

Each device has specific strengths, and the best protection strategy often involves a combination of devices:

- AVR + SPD for labs or offices,

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- UPS + SPD for IT and sensitive research equipment,
- Smart inverter systems for overall voltage protection in solar-powered infrastructures.

A hybrid approach ensures comprehensive protection while optimizing cost, performance, and compatibility with solar systems.

The outcome of the simulation and performance testing is a comprehensive report detailing the effectiveness of each protection device in handling real-world voltage disturbances. Key performance indicators (KPIs) such as response time, voltage stability, equipment protection, and system integration are used to form conclusions about which devices are most suitable for the university's specific needs.

Validationsof Research Results

The goal of this section is to validate the results obtained from the simulation and performance testing phase and provide actionable recommendations for improving voltage protection in solar-powered university facilities.Validation ensures that the chosen voltage protection devices function effectively in real-world conditions, while recommendations will guide stakeholders in implementing or upgrading protection strategies.

Validation Process

The validation process is critical to ensure that the results from the simulations and physical tests are applicable to the actual operating environment of the university facilities. The process involves:

Comparison with Real-World Data

- Data obtained from the simulations and test setups is compared with real-world performance data from the university's power system. This could include historical data on voltage fluctuations, equipment failures, or power quality issues within the campus.
- If available, feedback from university staff regarding past power disruptions and equipment performance can provide context for interpreting the test results.

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Cross-Validation with Industry Standards

The performance of the protection devices is cross-validated against industry standards and guidelines, such as:

- IEEE 1100 – Powering and grounding sensitive electronic equipment.
- IEC 61000 – Electromagnetic compatibility standards, including power quality and voltage disturbances.
- Solar Power System Standards – To ensure the integration of protection devices with solar inverters and overall system stability.
- The alignment with these standards helps ensure that the devices selected meet the technical requirements necessary for safe, reliable operation in a university environment.

Field Trials and Real-Time Monitoring

If feasible, a pilot or field trial can be conducted in a live university facility to test the performance of the protection devices under actual operating conditions. This would involve:

- Installing selected devices on a small-scale section of the facility's power network.
- Monitoring the performance and effectiveness in real-time during typical power disturbances (e.g., storms, grid fluctuations).
- Collecting data on the device's ability to stabilize voltage and protect sensitive equipment.

Conclusion: This study set out to analyze AC voltage protection for solar-based university facilities, with the aim of investigating the roles of voltage protection devices in stabilizing the AC supply for sensitive equipment. Based on the findings, it is evident that while solar energy offers a sustainable and reliable alternative to conventional grid power, it is not without operational challenges. Voltage instability remains one of the most critical issues affecting the

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performance and longevity of sensitive academic and research equipment in university environments.

The research established that voltage protection devices are indispensable in safeguarding solar-based power systems. Devices such as surge protectors, automatic voltage regulators, circuit breakers, and uninterruptible power supplies each play unique roles in mitigating the adverse effects of voltage disturbances. However, the study concludes that no single device provides complete protection. Instead, a layered or integrated approach that combines multiple devices offers the most effective solution for stabilizing AC supply.

Furthermore, it was concluded that the application of appropriate voltage protection measures significantly enhances the reliability of solar installations in universities. This not only protects sensitive equipment from damage but also ensures uninterrupted teaching, research, and administrative operations. Ultimately, the deployment of robust protection systems is a strategic investment that extends the lifespan of equipment, reduces maintenance costs, and improves the overall efficiency of solar-based energy facilities.

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