# Challenges of PV Grid Synchronization: A Case Study of Bangweulu Solar Plant and CEC Solar Plant in Zambia

**Mr. Francis Kafata**[1], **Mr. Ebert Mwala**[2]

[1]Lecturer/Engineer, Engineering, Zambia University College of Technology
[2]Engineer, Engineering, Zesco

## Abstract

Grid synchronization of photovoltaic (PV) systems is critical for ensuring stable and reliable power delivery, especially in regions with growing renewable energy adoption. This paper examines the challenges faced by the Bangweulu Solar Plant and the Copperbelt Energy Company (CEC) Solar Plant in Zambia, highlighting key synchronization issues that hinder optimal grid integration. Through detailed analysis, the study identifies factors such as grid instability, power quality disturbances, and varying load demands as primary challenges. Advanced monitoring tools and data-driven insights are used to evaluate the impact of these challenges on system performance and compliance with grid codes. Additionally, the paper explores potential mitigation strategies, including advanced control techniques and infrastructure upgrades, tailored to the local context. The findings aim to inform stakeholders and contribute to the broader discourse on enhancing PV grid integration in sub-Saharan Africa.

**Keywords:** 1. PV Grid Synchronization, 2. Bangweulu Solar Plant, 3. CEC Solar Plant, 4. Solar Energy in Zambia, 5. Synchronization Control

## 1.1 INTRODUCTION

The integration of photovoltaic (PV) systems into the power grid has emerged as a pivotal component of the global energy transition towards sustainable and renewable energy sources. As countries strive to meet increasing energy demands while reducing carbon emissions, solar energy systems, such as those implemented at the Bangweulu Solar Plant and the Copperbelt Energy Company (CEC) Solar Plant in Zambia, play a vital role in diversifying energy portfolios.

In the face of climate change, environmental degradation, and the urgent demand for sustainable development [1, 2], renewable energy sources such as solar power offer viable and promising solutions. The escalating concerns about climate change, caused by human-induced emissions of pollutants from thermal power plants, have rendered significant investments in traditional fossil-fuel-based power system infrastructures increasingly unappealing [3]. However, the effective synchronization of PV systems with the power grid remains a complex challenge, particularly in regions with weak grid infrastructure and dynamic operating conditions.

Grid synchronization involves aligning the frequency, voltage, and phase of the PV system with the grid to ensure seamless energy exchange and stability. Despite advancements in PV technology, challenges such as grid instability, fluctuations in solar irradiance, and load variations often compromise synchronization, leading to power quality issues, operational inefficiencies, and potential non-compliance with grid codes [4]. In sub-Saharan Africa, these challenges are exacerbated by aging grid infrastructure, limited access to advanced grid management tools, and rapid growth in energy demand.

This paper presents a case study of the Bangweulu and CEC Solar Plants, two significant PV installations in Zambia, to investigate the technical and operational challenges of PV grid synchronization. By leveraging field data and technical analyses, the study identifies critical synchronization issues, evaluates their implications for grid performance, and proposes practical solutions. The findings not only shed light on the unique synchronization challenges in Zambia but also provide insights relevant to similar contexts across the region.

The subsequent sections of this paper detail the methodology, case study findings, and potential strategies to enhance PV grid synchronization, offering valuable perspectives for researchers, practitioners, and policymakers working to advance renewable energy integration.

## 2.1 BACKGROUND

### 2.1.1 GRID SYNCHRONISATION

Grid synchronization involves the solar inverter aligning the electricity it produces with the grid it is connected to [5]. Grid synchronization is a critical process in integrating renewable energy systems, such as photovoltaic (PV) and wind energy, into the existing power grid. It ensures that these systems operate in harmony with the grid by aligning their voltage, frequency, and phase angle with the grid's parameters. This alignment is crucial to maintain power quality, system stability, and efficient energy transfer.

Managing solar PV systems is challenging due to their intermittent nature, necessitating operation within the constraints of grid connection. Accurate and rapid assessment of frequency and phase angle is crucial during grid synchronization [6]. This task becomes more complex due to transients, such as phase shifts and harmonics, caused by non-linear loads in the electrical network. Accurate frequency estimation is essential for ensuring power system stability, maintaining power quality, and achieving effective grid synchronization.

In conventional power systems, synchronization was primarily managed by large, centralized generators that inherently operated at grid frequency. However, the advent of distributed renewable energy sources, characterized by intermittent and variable output, has introduced complexities in maintaining synchronization. Solar PV systems, in particular, require sophisticated control mechanisms due to their dependence on variable solar irradiance.

During grid synchronization, a renewable energy system must detect the grid's frequency and phase angle accurately and in real-time. Any misalignment can lead to power quality issues, instability, and even damage to the equipment. Effective grid synchronization is essential not only for the reliable integration of renewable energy but also for meeting grid codes and standards, which mandate strict compliance with power quality and system stability requirements. As renewable energy penetration continues to grow, the development of robust and efficient grid synchronization techniques remains a critical area of research and innovation.

### 2.1.2 GRID SYNCHRONIZATION CHALLENGES

The renewable energy sector faces numerous challenges, such as the intermittency of solar energy sources [7], substantial initial investment costs [8], and complications related to energy storage and grid integration [9]. Among the renewable energy systems, Solar energy is the most frequently utilized renewable energy source due to its widespread availability [10]. However, grid-connected renewable energy projects encounter several challenges related to their variable generation rates, including issues with compatibility with the grid utility [10].

Other challenges in grid synchronization include fluctuations in grid frequency caused by variations in demand and supply, which are especially common in regions with less stable power systems. Solar PV systems must respond swiftly to these changes to prevent instability and maintain proper synchronization. Similarly, voltage fluctuations, often triggered by sudden changes in solar irradiance or load conditions, can hinder PV systems' ability to synchronize while upholding power quality.

In weak grids, characterized by low short-circuit ratios, synchronization becomes even more challenging due to reduced system strength and heightened sensitivity to voltage and frequency fluctuations. Additionally, errors in frequency estimation can result in incorrect inverter settings, leading to instability or potential disconnection from the grid.

Traditional synchronization methods, such as Phase-Locked Loops (PLLs), often struggle to perform effectively under dynamic grid conditions, highlighting the need for more robust and adaptive control strategies. Furthermore, the high costs of advanced synchronization equipment, coupled with the technical expertise required for their implementation and maintenance, pose significant barriers, particularly in developing regions.

Also challenges such as phase shifts, harmonics, and transients often caused by non-linear loads or grid disturbances, complicate the synchronization process. Modern synchronization methods rely on advanced algorithms and technologies, such as phase-locked loops (PLLs) and Model Predictive Control (MPC), to address these challenges. These methods aim to improve response time, accuracy, and robustness under dynamic grid conditions, including frequency variations and grid faults.

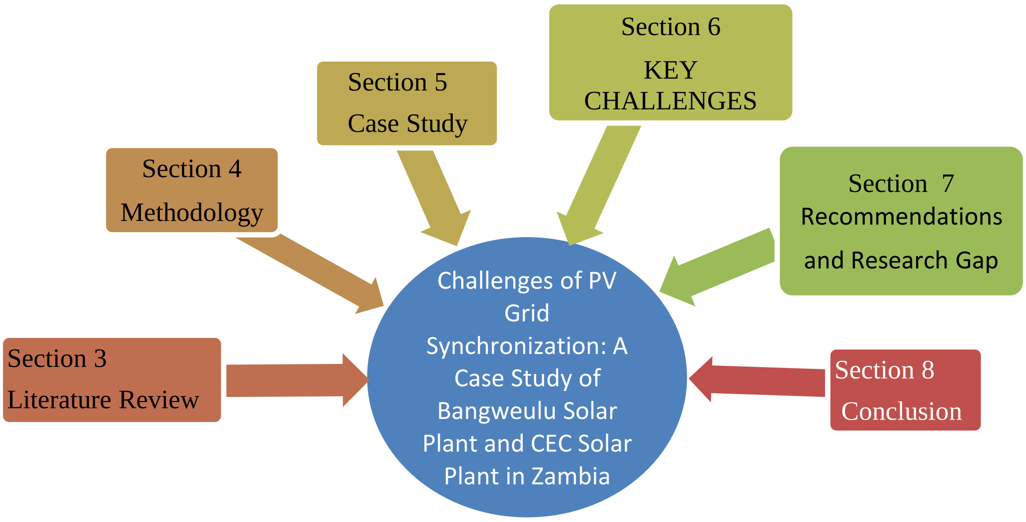
### 2.1.3 OBJECTIVES OF THE STUDY AND ITS RELEVANCE TO STAKEHOLDERS.

1. Investigate the specific technical and operational challenges encountered during the grid synchronization of PV systems at the Bangweulu Solar Plant and CEC Solar Plant in Zambia.
2. Evaluate the impact of factors such as frequency variations, harmonics, transients, and phase shifts on system performance.
3. Review and propose effective techniques to overcome synchronization challenges.
4. Improved understanding of synchronization challenges to optimize plant performance and reduce downtime.

### 2.1.4 ORGANISATION OF THE PAPER

The remainder of this paper is structured as follows: Section 3 presents literature review. Section 4 presents the methodology. Section 5 presents Case studies. Section 6 presents key challenges. Section 7 presents recommendations. Finally, Section 8 presents the conclusions of the paper. Figure 1 presents the summary of paper organisations.

**Figure 1 Summary of organisation of paper**



## 3.1 LITERATURE REVIEW

The shift from traditional generators to inverter-based distributed generation (DG) and renewable energy sources (RES) has introduced significant technical challenges, such as low inertia, frequency instability, and harmonic distortion [11]. Addressing these challenges requires robust and efficient control strategies for inverter-based systems to ensure a stable and reliable grid interface.

Grid-connected inverters operating under weak grid conditions or severe fault events face the risk of losing synchronism with the external grid and neighboring inverters. This has driven growing interest in studying synchronization mechanisms and developing models and tools to predict transient stability in inverter-based systems [12].

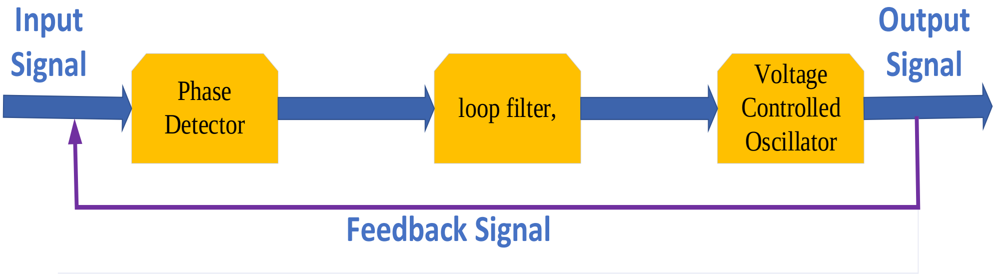
Unlike traditional synchronous machines, the transient response of inverters is primarily governed by their control structures [13]. Historically, small power generation units like wind turbines (WTs) and photovoltaic (PV) systems were allowed to disconnect from the grid during abnormal conditions, as the impact on grid stability was minimal. However, as the penetration of RES increases, grid disconnection during faults can significantly affect grid reliability, stability, and availability [14].

Accurate synchronization with grid voltage at the point of common coupling (PCC) is a critical challenge for power inverters [15, 16]. While grid voltage waveforms are generally sinusoidal and balanced under normal conditions, they can become unbalanced and distorted due to faults and nonlinear loads. In such situations, grid-connected converters must maintain synchronization to remain connected, support grid services, and ensure stable operation [17].

To address synchronization challenges, innovative methods such as a positive-sequence detection mechanism using a Decoupled Double Synchronous Reference Frame Phase-Locked Loop (DDSRF–PLL) have been developed [18]. This method eliminates common detection errors encountered in traditional Synchronous Reference Frame PLLs (SRF–PLL).

A fundamental PLL circuit typically includes three key components: a phase detector, a loop filter, and a Voltage Controlled Oscillator (VCO). The Phase Detector (PD) identifies the error between the input signal and the output from the internal oscillator. The Loop Filter (LF) removes high-frequency AC components from the output signal. Meanwhile, the Voltage Controlled Oscillator (VCO) generates the phase angle.

**Figure 2 Basic structure of PLL**



The Synchronous Reference Frame PLL (SRF-PLL) [19, 20] is a widely used method in power system applications. However, its performance can degrade in the presence of voltage imbalances and harmonic distortions. While reducing the bandwidth of PLLs can address this issue, it is not always feasible for certain applications, such as grid-connected distribution generation systems [21] and Low Voltage Ride Through (LVRT) requirements [22]. To address this, an additional Low Pass Filter (LPF) is often incorporated into the control loop. Nonetheless, this approach has three significant limitations: (1) it only approximates the amplitude and phase angle of the positive sequence component rather than providing exact values; (2) it yields distorted and unbalanced positive sequence voltages; and (3) it significantly reduces the system's dynamic response. Various synchronization techniques have been proposed to enhance SRF-PLL performance. For instance, the three-phase Enhanced PLL (EPLL), which uses four signal phases and symmetrical components, offers improved accuracy under unbalanced grid conditions and can reduce, though not entirely eliminate, the effects of harmonic distortion.

The Moving Average Filter (MAF)-PLL [23] features a simplified structure and offers robustness against unbalanced and distorted source voltages. However, it suffers from minor inaccuracies when there are deviations in the grid frequency. Additionally, the primary drawback of the MAF is its slow dynamic response.

Recently, a new method called the Frequency Locked Loop (FLL) [24, 25] has been introduced. The FLL focuses on estimating the frequency of the input signal. Because the frequency remains stable despite sudden changes in the main voltage, the FLL offers superior performance in terms of harmonic rejection and phase angle transients compared to PLL-based algorithms.

The Dual Second Order Generalized Integrator Frequency Locked Loop (DSOGI-FLL) was introduced in [25] and demonstrated effective performance in estimating the fundamental component of the main voltage. However, its performance deteriorates with heavily distorted voltages [24], to address this limitation, the Multi Second Order Generalized Integrator Frequency Locked Loop (MSOGI-FLL) was proposed in [24], The MSOGI-FLL employs multiple DSOGI units to handle each harmonic component and utilizes a Harmonic Decoupled Network (HDN) to mitigate harmonic effects.

A phase-locked loop (PLL) is a commonly employed technique for grid synchronization, capable of enduring power system oscillations. However, its sensitivity can influence the precision of the reference signal it produces. Traditional PLLs incorporate a feedback loop filter (LF) to track the grid's frequency and phase, thereby improving steady-state performance even in demanding grid conditions [26]. In [27], a power line communication (PLC) system is designed and implemented, utilizing the loop resonance characteristics of an entire DC-PV string. In [28] research proposes a ring topology for power line communication (PLC) by leveraging PV strings' wiring characteristics. This closed-loop design supports resonance conditions and enables practical communication using the PV series string as the physical transmission medium. Some researchers have utilized PLC for various applications in solar plants. In, PLC is applied as an automatic transfer switch (ATS) to manage the selection of electrical connection circuits. In PLC facilitates data transmission from the photovoltaic plant through the AC power line. Reference proposes a PLC-based system to prevent islanding by controlling connection and disconnection devices. Meanwhile, utilizes a PLC-driven communication and control system for managing cascade inverters.

Similar to [29], the study investigated the limitations of traditional synchronization methods, particularly power line communication synchronization (PLS), in managing the fluctuations of renewable energy sources. It emphasized that PLS techniques might struggle to achieve the required synchronization accuracy during abrupt changes in generation patterns, as commonly observed in solar and wind energy systems.

The Model Predictive Control (MPC) technique has gained significant attention as a powerful controller in power electronics and drive systems due to its numerous advantages. These include its ability to handle nonlinear systems directly in the time domain, its flexibility in defining and adjusting cost functions to select control objectives or incorporate additional constraints, and its capability as a multi-variable, multiple-input multiple-output (MIMO) controller [30].

As noted in [31], MPC leverages model-based optimization to automatically determine the control law, emphasizing its adaptability and the benefits of explicitly utilizing system models in engineering applications. This predictive and constraint-handling capability positions MPC as a highly effective strategy for optimizing the performance of multilevel inverters in dynamic photovoltaic (PV) grid environments, where robustness and adaptability to varying conditions are critical.

## 4.1 METHODOLOGY

### 4.1.1 The Research Design

The research used a cross-sectional survey design adopting qualitative methodology to a smaller extent and quantitative method to obtain evidence.

### 4.1.2 Personal Interviews

The research also carried out personal interviews informally as a way of collecting information for the research. Personal interviews provided the most direct evidence of how performance of the solar plants. This involved collection of data through oral questioning of respondents. Structured questions were used as a guide aimed at soliciting useful data.

### 4.1.3 Data Analysis

The qualitative information that was obtained from the questionnaires, interviews and documents was analysed and was put into themes. On the other hand, quantitative data was analysed through the use of statistical software called STATA and tools such as frequency tables, pie charts and bar charts used

### 4.1.4 Data Collection

Secondary data for the research was obtained through the use of sources such as; the researcher analysed journals, past researches and the internet. This collection method has been used mostly in the Literature Review. Primary data was collected from the field using three sets of survey questionnaires.

## 5.1 CASE STUDY

### 5.1.1 COPPERBELT ENERGY CORPORATION (CEC) SOLAR PLANT AND BANGWEULU SOLAR PLANT

CEC is a leading Zambian power utility that specializes in the generation, transmission, distribution, and supply of electricity. CEC primarily serves mining companies in Zambia's Copperbelt region but has also expanded into renewable energy projects, including solar power initiatives. The company currently operates two major solar power plants: Riverside Solar Power Station located in Kitwe, this facility has an installed capacity of 34.5 megawatts (MW) and Itimpi Solar Power Station situated in Kitwe, with installed capacity of 54 megawatts (MW).

The Bangweulu Solar Power Plant is one of Zambia's flagship renewable energy projects, located in the Lusaka South Multi-Facility Economic Zone. It is a 54.3 MWp solar photovoltaic power plant developed under Zambia's Scaling Solar Program, which is supported by public-private partnership involving the Industrial Development Corporation (IDC) of Zambia and private investors. It plays a key role in diversifying Zambia's energy mix, which historically relies heavily on hydroelectric power, and contributes to increasing the country's energy security and resilience against climate-related risks such as droughts. It is part of Zambia’s efforts to expand renewable energy sources and reduce energy deficits.

### 5.1.2 GRID SYNCHRONIZITION TECHNOLOGY

The two solar energy plants use inverters connected in strings through a utility transformer. Both plants incorporate voltage and frequency regulation systems in their grid synchronization schemes. The inverters are designed to adapt to minor grid fluctuations and provide support by injecting reactive power during disturbances. Power line communication (PLC) systems is employed to monitor, control, and manage synchronization processes and grid interactions in real time. This technology utilizes existing electrical power lines to transmit data, facilitating communication between devices without the need for additional wiring. In solar power plants, PLC can be employed for monitoring and controlling various components, including inverters and grid interface systems. It plays a crucial role in the Smart Grid by facilitating efficient sensor networking and network control within the power distribution system. Both plants are required to comply with Zambia Electricity Supply Corporation’s (ZESCO) grid codes, ensuring compatibility with the national grid which involves strict adherence to parameters such as: Voltage limits, Frequency ranges and Harmonic distortion levels for smooth integration in the grid.

## 6.1 KEY CHALLENGES OBSERVED

The primary problem with the synchronization method described above is the ability of PV systems to continue operating even when the grid is experiencing abnormal circumstances. Both plants face challenges related to inverter technology control and grid stability. Although Power Line Communication (PLC) holds promise for grid synchronization in power systems, it is crucial to conduct studies that address its susceptibility to noise, signal attenuation, and possible interference from other devices on the power line.

Inverter performance is crucial for the efficient operation of solar power plants, as they convert the direct current (DC) generated by solar panels into alternating current (AC) compatible with the electrical grid. Both the Bangweulu Solar Plant and CEC's solar facilities in Zambia have encountered challenges related to inverter performance, primarily due to environmental factors and operational demands. Temperature variations due to climate changes, characterized by significant temperature fluctuations, can adversely affect inverter components. High temperatures may lead to overheating, reducing efficiency and potentially causing component failures. Inverters being subjected to loads beyond their designed capacity which often cause overheating and accelerate wear and tear, leading to reduced lifespan and increased failure rates. Fluctuations in grid voltage and frequency can challenge inverters by straining their synchronization capabilities, potentially causing operational issues.

PLC systems are significantly affected by electrical noise and interference from other devices on the power line, which degrades signal quality and synchronization accuracy. It was also observed that the signal strength of PLC diminishes over long distances and through various electrical components, often which results in poor communication quality and reduced effectiveness in maintaining synchronization. Due to limited bandwidth, PLC often restricts the amount of data transmission, which can impact the speed and accuracy of synchronization. The complex network topology of power lines in large solar plants complicates PLC signal routing, potentially causing signal degradation over long distances. Fluctuations in power loads change the impedance of power lines, impacting the transmission characteristics of PLC signals and causing communication instability. Maintaining grid stability with intermittent solar power is challenging, as the variability in solar generation due to weather conditions impacted grid stability. In [32] observed that intermittent nature of solar photovoltaic (PV) systems presents operational and technical challenges, affecting the reliability and stability of the network. Achieving a stable voltage profile with minimal fluctuations requires a consistent power source capable of adapting to changes within the network.

## 7.1 RECOMMENTATIONS

### 7.1.1 MITIGATION STRATEGIES

Installing advanced cooling mechanisms helps maintain optimal operating temperatures for inverters, thereby improving performance and longevity although this comes at an expense to the organisation. It is also often recommended to implement effective load management strategies that prevents overloading, ensuring inverters operate within their specified capacity. Equipping inverters with advanced grid support functionalities, such as voltage and frequency regulation, enhances their ability to handle grid instabilities. Transformer-less PV inverters are widely adopted to attain higher efficiency for integrating the PV systems into the grid. PLLs provide precise frequency and phase synchronization by continuously adjusting the output to match the grid's frequency and phase. They are well-suited for handling rapid changes in renewable energy sources and can effectively maintain synchronization even in dynamic conditions. Ethernet offers high bandwidth and low latency, which can improve synchronization accuracy and speed. It is less susceptible to noise and interference compared to PLC. Using dedicated communication channels, such as fibre optics or separate communication lines, can provide high reliability and bandwidth for synchronization tasks. In general, PLLs are highly favored for their precision and adaptability in synchronizing renewable energy sources with the grid, while Ethernet and Modbus offer robust communication solutions that enhance overall synchronization and control.

The work also proposals for research in advance inverter topologies such multilevel inverters and advance grid control technologies such as predictive control which have shown potential in mitigating these challenges despite being new in the field of renewable energy. In [33] observed that critical aspect of power electronic inverters is ensuring stability when integrating PV with the main grid. Additionally, delivering reliable electric power requires addressing the challenges of grid integration of PV energy systems, which are effectively managed using advanced control techniques.

### 7.1.2 RESEARCH GAP

This is one of the first research to address the challenges of integration of solar energy into the grid at the Copperbelt Energy Corporation (CEC) and Bangweulu Solar Power Plant in Zambia. Currently Zambia is struggling to supply electrical energy due to the effects of droughts as a result of dependence on hydropower. However, the initiatives taken to integrate solar energy into the grid will help mitigate the challenge of energy shortage. These solar plants act as pilot projects in the quest to integrate solar energy to the grid for the first time. Hence the research reviewed the challenges that the country may face as more solar plants are coming on board. Which calls for further research in the field of renewable energy integration to achieved reliable and stable grid system.

## 8.1 CONCLUSION

The integration of solar energy into Zambia's grid system, particularly through the Copperbelt Energy Corporation (CEC) and Bangweulu Solar Power Plant, presents both significant opportunities and challenges. As Zambia faces energy shortages exacerbated by droughts and its dependence on hydropower, the introduction of solar energy offers a promising solution to enhance energy security and reduce the nation's reliance on a single energy source. However, the integration of photovoltaic (PV) systems into the grid introduces challenges related to grid stability, synchronization, and the variability of solar power generation. These issues require careful consideration of control techniques, grid infrastructure, and ongoing research to ensure smooth integration and reliable operation.

As Zambia continues to expand its solar energy capacity with more plants coming online, the findings from this study emphasize the need for targeted strategies to address synchronization challenges, improve grid resilience, and optimize the performance of renewable energy systems. This research provides a valuable foundation for future studies and highlights the importance of further research in renewable energy integration to achieve a stable, reliable, and sustainable grid system in Zambia. By addressing these challenges, Zambia can pave the way for a more diverse and resilient energy future.

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