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Master-Slave Synchronization in Off-Grid Solar Microgrids: Genset and Inverter Configurations

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ABSTRAK

Penelitian ini menganalisis kinerja sinkronisasi microgrid surya AC off-grid untuk membandingkan konfigurasi master-slave berbasis genset dan inverter master. Evaluasi stabilitas dan kualitas daya dilakukan melalui simulasi MATLAB/Simulink serta validasi eksperimental. Hasil pengujian menunjukkan konfigurasi genset-master menghasilkan sinkronisasi stabil (220V/50Hz), sementara konfigurasi inverter-master mengalami ketidakstabilan tegangan di awal. Namun, dengan mengoptimalkan rasio kapasitas daya antara unit master dan slave menjadi 10:1 serta menerapkan modulasi PWM yang dirancang dengan tepat, sistem berhasil mencapai operasi yang stabil. Sistem pemantauan berbasis IoT yang menggunakan ESP32 dan sensor PZEM-004T menyediakan data real-time untuk memvalidasi temuan ini, yang mengonfirmasi bahwa meskipun konfigurasi master berbasis inverter layak digunakan, diperlukan parameter desain yang presisi untuk memastikan sinkronisasi yang handal.

***Kata kunci**: Konfigurasi master-slave, Sinkronisasi, Inverter Terhubung Jaringan (Grid-Tied Inverter/GTI), dan Internet of Things (IoT).*

ABSTRACT

The research analyzes the synchronization performance of off-grid solar AC microgrids by comparing genset-based and inverter-based master-slave configurations. Stability and power quality evaluations were conducted through MATLAB/Simulink simulations and experimental validation. Test results show that the genset-master configuration produces stable synchronization (220V/50Hz), while the inverter-master configuration experiences initial voltage instability. However, by optimizing the power capacity ratio between the master and slave units to 10:1 and implementing a properly designed PWM modulation, the system successfully achieves stable operation. An IoT-based monitoring system using ESP32 and PZEM-004T sensors provides real-time data to validate these findings, confirming that while the inverter-based master configuration is feasible, precise design parameters are required to ensure reliable synchronization.

***Keywords**: Master-slave configuration, Synchronization, Grid-Tied Inverter (GTI), dan Internet of Things (IoT).*

1. INTRODUCTION

Based on current literature, solar cells are an important technology for electrical energy conversion, which serves as a core component of Photovoltaic Power Plant (PVPP) systems. NPP configurations are generally categorized into two main architectures: on-grid and off-grid. On-grid systems are integrated with the national electricity grid (PLN), which acts as a nearly unlimited energy buffer, allowing users to export excess electricity generated from their solar installations to the utility grid. In contrast, off-grid systems or microgrids operate independently, relying entirely on local energy sources such as solar panels and diesel generators. PV-based peer-to-peer microgrid system configurations have two options: DC peer-to-peer, or AC peer-to-peer microgrids. The advantage of AC peer-to-peer microgrids is that they require relatively few connecting cables because the system operates at relatively high and commonly used voltages. Therefore, this configuration is very important for remote or rural areas that do not have access to national electricity infrastructure. Furthermore, it is hoped that if this AC peer-to-peer microgrid can be successful, the system can develop into a standalone off-grid rural electricity grid or as an energy-independent village.

This study investigates an off-grid microgrid architecture featuring a PVPP configuration integrated with a Grid-Tied Inverter (GTI) and a Maximum Power Point Tracker (MPPT) to manage power distribution based on load demand. In this setup, the GTI operates as a follower unit synchronized to a master inverter of a predetermined capacity. This modular design supports scalable microgrid deployment, enabling the integration of multiple PVPP units with GTI-based inverters to expand system capacity.

This work focuses on designing a microgrid system whose core function is the synchronized control between inverters to continuously supply AC loads with optimal power quality. The electrical system comprises a pure sine-wave inverter and GTI, which are controlled to achieve optimal energy conversion based on solar panels and battery storage as primary energy sources. The growing demand for renewable and sustainable energy has accelerated the use and study of photovoltaic (PV) systems across the residential and industrial sectors **(Heydari et al., 2023)(Makkiabadi et al., 2021).** The transition to solar energy is supported by Indonesian government regulations **(Sistriatmaja et al., 2024) (Yudiartono et al., 2023).** However, there are restrictions on the trading of excess energy generated from rooftop solar systems, as stipulated in Minister of Energy and Mineral Resources Regulation No. 26/2021. In the Indonesian context, practical implementations of PV systems have also been studied, such as the design of roof-mounted PV systems for public facilities **(Sartika et al., 2023)**. The impact of this change has also encouraged the development of off-grid PV systems capable of providing stable power in areas without grid connectivity.

Off-grid PV systems are designed for rural communities where expanding the national electricity grid is technically and economically challenging. Research on the resilience of solar mini-grids has demonstrated their crucial role in supporting sustainable energy access in developing nations (**Adu-Poku et al., 2023).** The main challenge in these systems is maintaining stable voltage, frequency, and waveform during use and installation. This can also ensure synchronization between resources to achieve reliable energy delivery and minimize system losses **(Huang et al., 2022) (Manahara et al., 2023), (Mardiyanto et al., 2022).** Several studies have explored inverter-based synchronization and control, such as Solanki et al. **(Solanki et al., 2018)** proposed an off-grid inverter capable of producing a pure sine wave AC output, **(Tan et al., 2020)** developed a single phase inverter with LC filtering to enhance output quality. The development of a solar power output monitoring system based on IoT technology has also been pioneered in previous research as a foundation for ensuring system confidentiality **(Mursid et al., 2018)**. Nrartha implemented an IoT-based monitoring system for off-grid PV plants, although without synchronized control among multiple inverters **(Nrartha et al., 2023)**. And in other studies The integration of IoT-based monitoring is essential for system efficiency, as modern control systems are increasingly applied to various fields, including energy generation **(Okokpujie et al., 2024)**. Despite these advances, synchronization between inverter based sources and mechanical generator-based systems remains insufficiently addressed.

This research investigates the synchronization dynamics of a hybrid master-slave microgrid integrating a master inverter, a grid-tied inverter (GTI), and a diesel generator to bridge this critical gap. The primary objective is to establish critical stability criteria for these configurations in off-grid environments. By quantifying the optimal power capacity ratio, this paper provides a robust design framework capable of delivering a stable 220 V, 50 Hz output, effectively ensuring power quality that meets the operational standards of the public utility grid.

2. METHODOLOGY

This study investigates synchronization performance in an off-grid solar microgrid configured under a master slave control scheme. The master device either a diesel generator or a pure sine wave inverter generates a 220 V, 50 Hz reference signal, while the Grid Tied Inverter (GTI) acts as a slave that follows the master’s voltage and frequency.

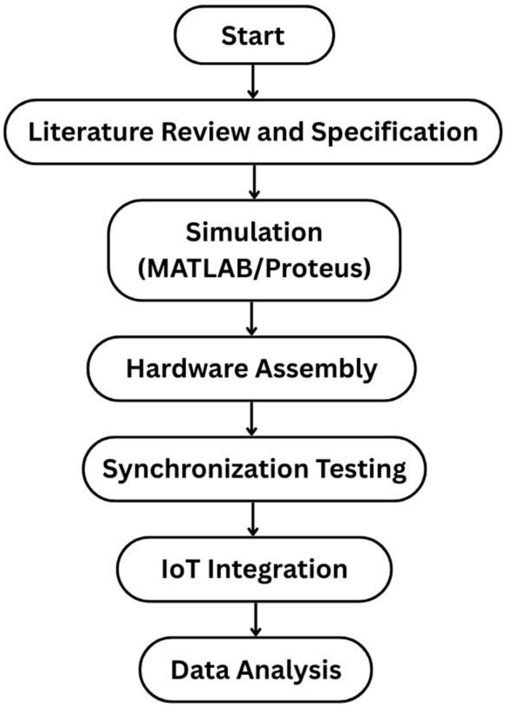

Figure 1. Flowchart of the synchronization stability assessment of master-slave microgrid configurations

Figure 1 illustrate the methodology flowchart and overview of the research workflow. The process consists of six sequential stages beginning with literature review and system specification, followed by simulation, hardware assembly, synchronization testing, IoT integration, and finally, data analysis and conclusion.

1. System Modeling and Simulation

In this scheme, system modeling is performed using MATLAB/Simulink software to predict system behavior and evaluate component stability prior to physical implementation. This simulation focuses on comparing the performance of the microgrid system across two main operational scenarios:

a. Inverter Configuration as Master: Testing the inverter's ability to provide standard voltage and frequency signals to a slave, a Grid Tie Inverter (GTI).
b. Genset Configuration as Master: Testing the use of a genset as the primary reference source, which is then synchronized with the GTI as a slave to supply power to the load.

2. Hardware Prototype Development

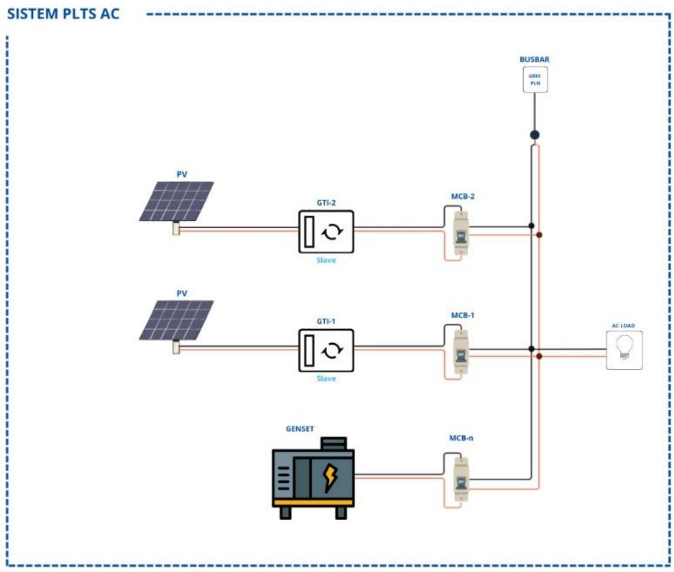

Figure 2. Microgrid design using a Master in the form of a Genset and a Slave in the form of a Grid Tie Inverter

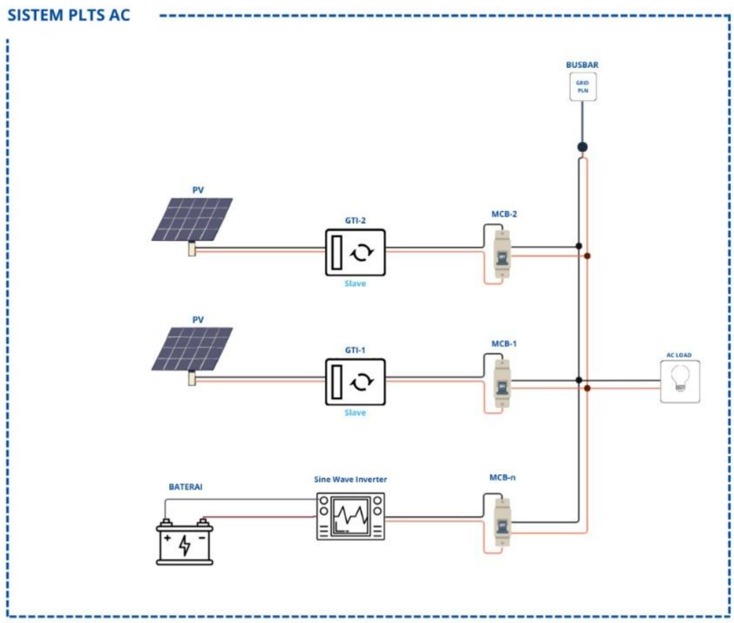

Figure 3. Microgrid design uses a Master in the form of an Inverter (pure and Hybrid) and a Slave in the form of a Grid Tie Inverter

The second phase involved the assembly of a laboratory-scale prototype as illustrated in Figure 2, a microgrid design that uses a diesel generator (genset) as the master. In this scheme, the genset provides a stable 220 V, 50 Hz reference signal due to its mechanical inertia, while Grid-Connected Inverters (GTIs) act as slave units synchronized with this reference to collectively supply the AC load. Furthermore, Figure 3 presents an alternative configuration where a pure sine wave inverter acts as the master, powered by multiple 12-volt batteries. This configuration places the GTIs as followers that must align their phase and frequency with the output of the master inverter. Operational success in this model depends heavily on precise design parameters, particularly the power capacity ratio between the master and slave units.

The hardware setup is further equipped with a monocrystalline solar panel rated at 38 V and 500 W to serve as the primary renewable energy source. Integrated with an MPPT system, these modules provide the necessary DC power to the GTIs and battery bank, facilitating empirical validation of the synchronization dynamics previously modeled in the simulation phase.

3. IoT-Based Monitoring
The final stage is the development of an IoT-based monitoring system for real-time data validation. Figure 4 illustrates the component and circuit design for this IoT system, which utilizes an ESP32 microcontroller as the central data acquisition unit integrated with a PZEM-004T sensor. This system automatically measures voltage, current, power, frequency, and power factor, then sends the data via Wi-Fi to a Blynk Cloud dashboard and Google Sheets for remote analysis and visualization.

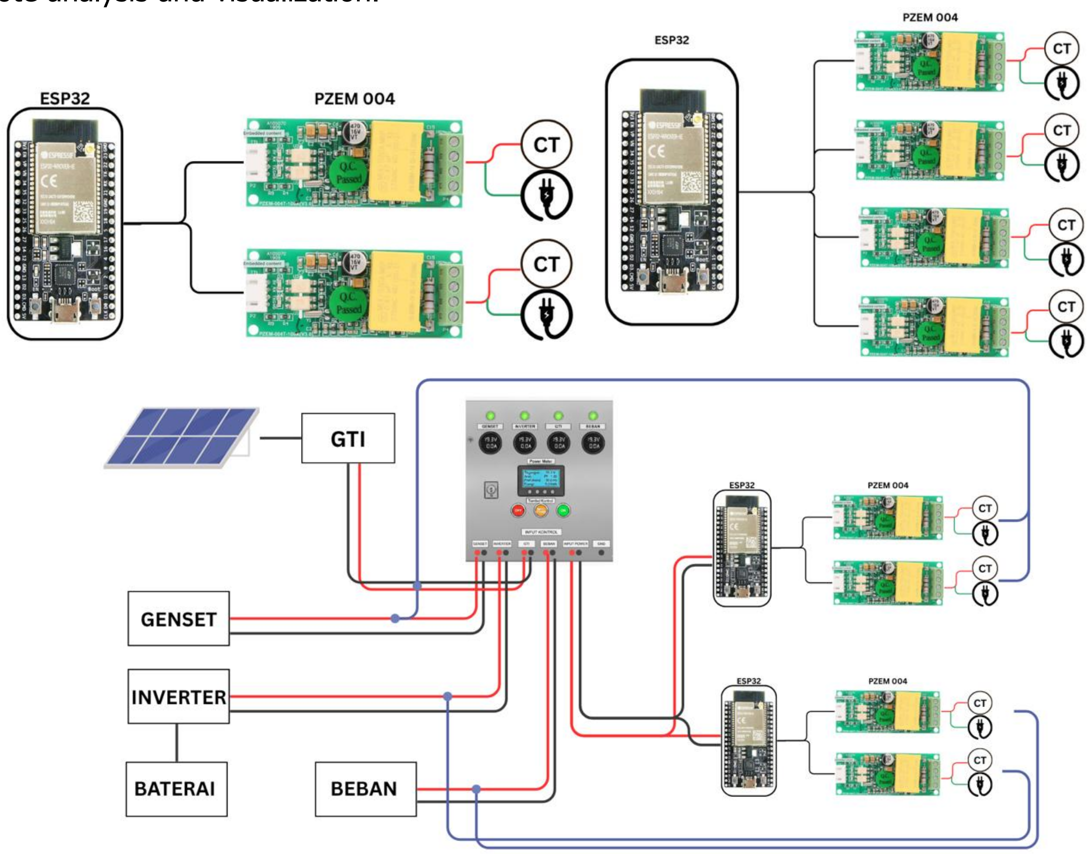

Figure 4. Component and circuit design for IoT

The system uses an ESP8266 microcontroller as the data acquisition unit. The PZEM-004T sensor is integrated at each strategic measurement point, namely the generator output channel, GTI output, and load. This sensor integration allows continuous monitoring of critical system parameters, including voltage (V), current (I), power (P), frequency (f), and power factor (PF). Sensor readings are then sent wirelessly via the internet to the Blynk cloud platform. This data logging mechanism is designed to store system performance records online. For further data processing and long-term trend analysis, data from the cloud is automatically integrated into a spreadsheet format, making it easier for the research team to evaluate system performance.

3. RESULTS AND ANALYSIS

The results of this study comprise both simulation and experimental evaluations conducted to analyze synchronization performance in an off-grid solar microgrid with a master slave control configuration. Two configurations were examined: (1) a diesel generator (genset) as the master and a GTI as the follower, and (2) a pure sine wave inverter as the master and a GTI as the follower.

3.1 Simulation Analysis

Simulation analysis was performed to evaluate the behavior of the microgrid system under two primary power source configurations. The simulations used Matlab-based Simulink. The simulations focused on the electrical system for interconnection and synchronous connection between master and slave power signal sources serving a shared load. Simulations were then performed to obtain an overview of the system voltages and currents, as well as the currents and voltages of each source.

1. Genset Configuration as Master

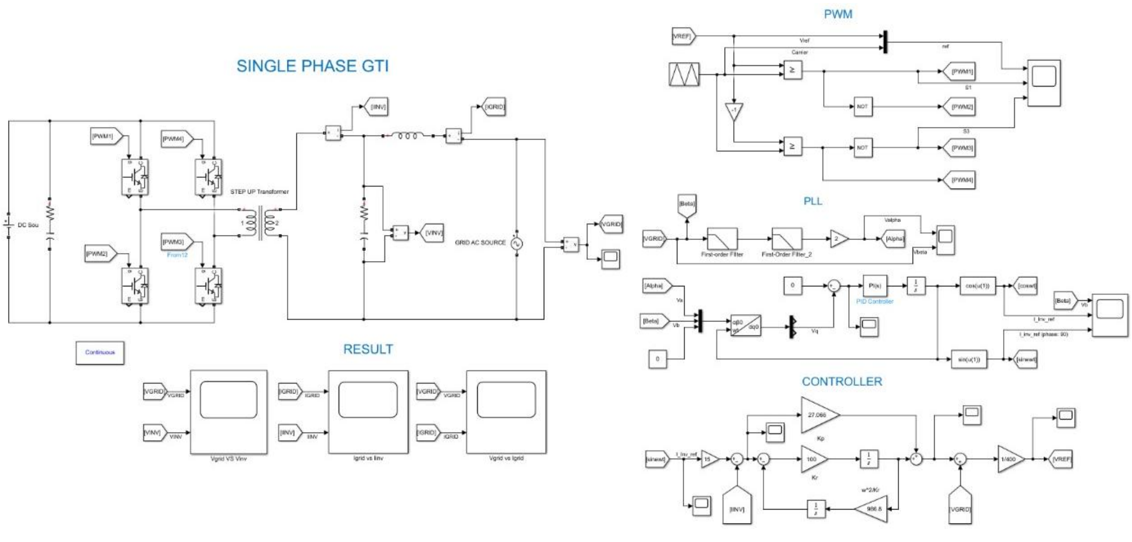

Figure 5. Simulation of Inverter controller on GTI

Figure 5 illustrates the GTI control system. This diagram presents a control architecture that integrates a Phase Locked Loop (PLL) as a crucial element to track the phase and frequency of the main source voltage in real-time. The reference signal obtained from the PLL is then processed using a Proportional-Integral (PI) controller that functions to minimize steady-state errors and maintain the stability of the inverter output voltage. The integration between the

PI controller output and the PWM (Pulse Wide Modulation) modulation in Figure 3 explains the GTI is able to adjust the MOSFET switching so that the inverter output voltage remains aligned with the grid voltage, thus synchronization can be achieved.

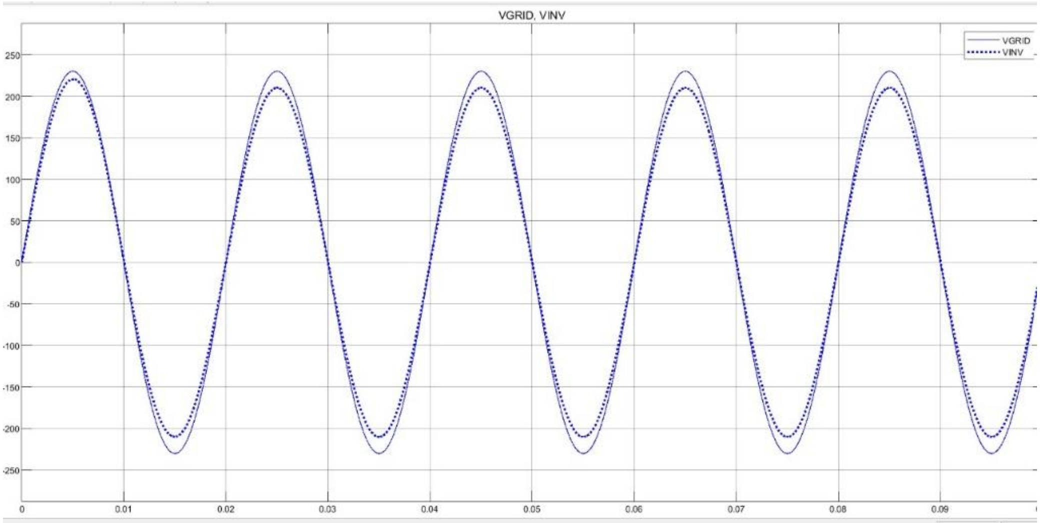

Figure 6. Simulation results when GTI connected to the network

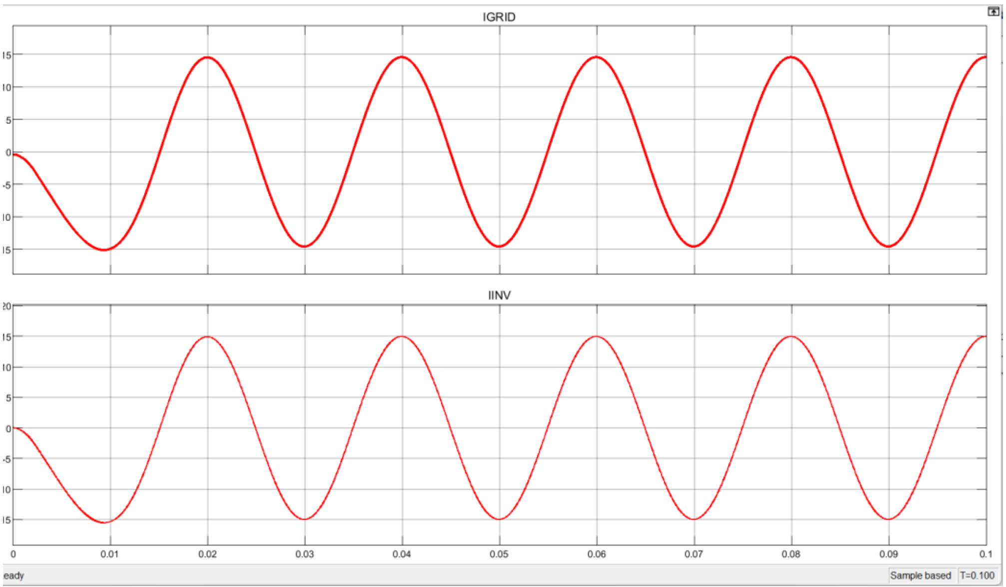

Figure 7. Simulation results of current on the network against GTI current

In the first testing, a genset was used as a master source capable of maintaining the system voltage at a constant amplitude of 220 V and a frequency of 50 Hz. Simulations in Figure 6 showed that the GTI could synchronize well with the genset, and the inverter voltage output was to be in phase with the grid voltage. and current analysis in Figure 7 revealed that the grid current was significantly affected by the current injection from the GTI, indicating that the GTI actively delivered power to the grid as soon as it was connected. This performance synchronization was further validated through testing with two GTIs synchronized to the genset, where the simulation results of the load current and output current of each GTI were consistent and stable as shown in Figures 8 and 9.

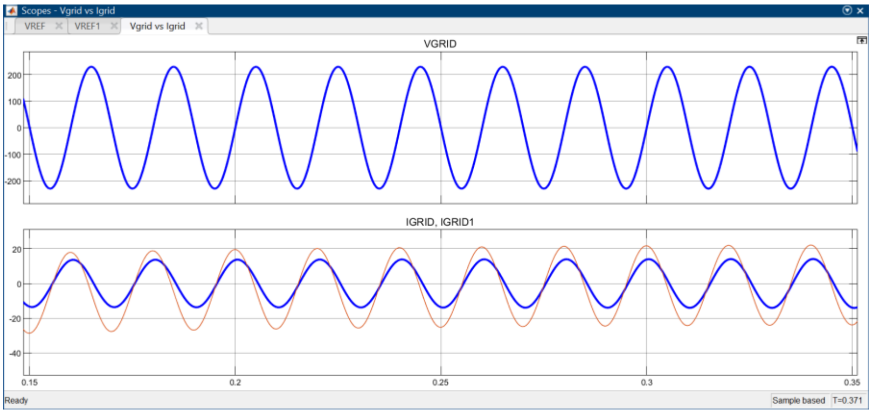

Figure 8. Simulation results of voltage on the grid and current from GTI sent to the grid

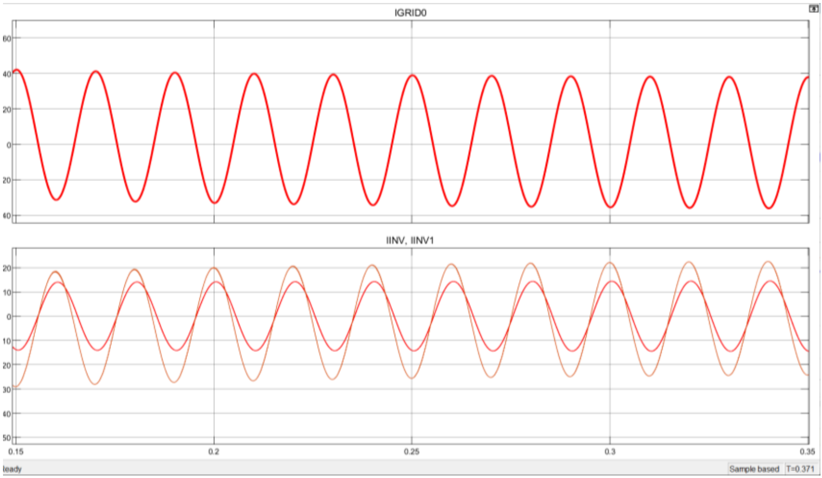

Figure 9. Simulation results of the current on the load and the current output by each GTI.

2. Inverter Configuration as Master

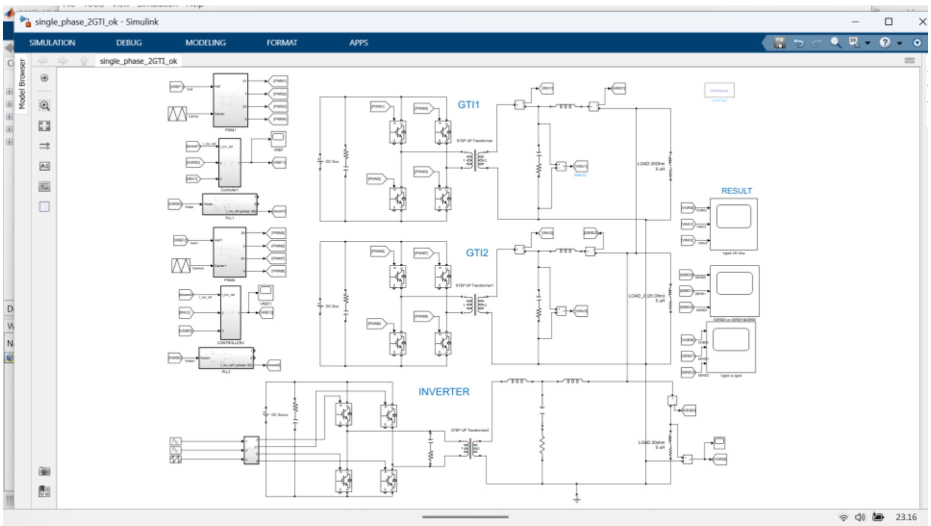

Figure 10. Simulation Model of Inverter as Master and GTI as Slave (Follower)

The next testing step evaluates the system performance by using the inverter as the master unit to replace the role of the generator, as illustrated in Figure 10. In this configuration, both the master and slave units (two GTI units) are supplied by energy from the battery, with the main objective of maintaining voltage stability at 220 V and a frequency of 50 Hz in the microgrid network.

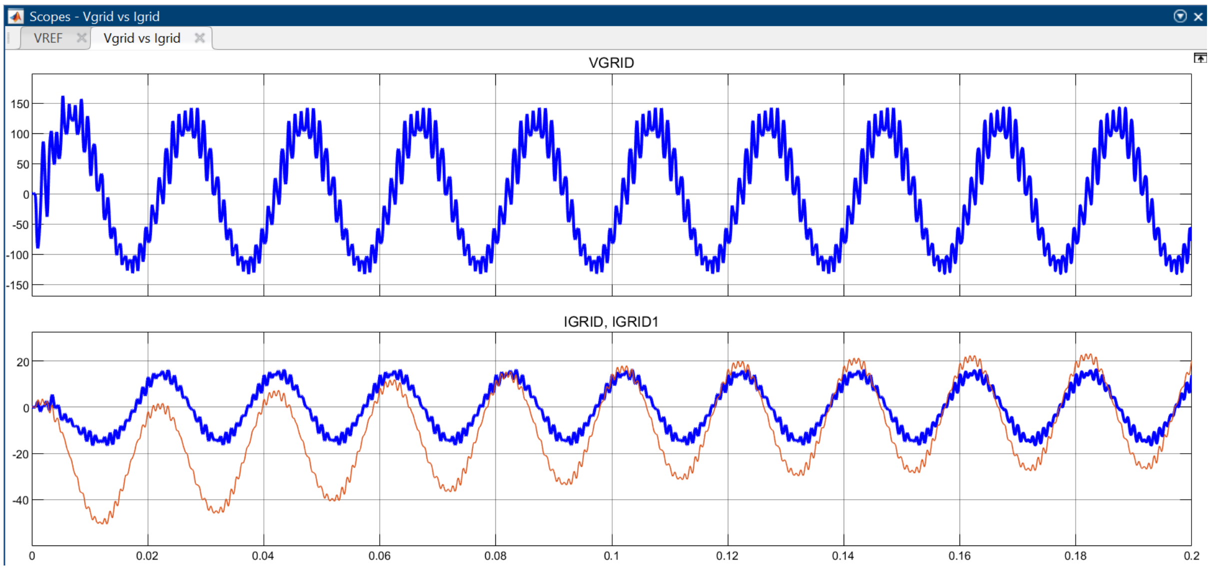

Figure 11. Simulation results of GTI system voltage and current

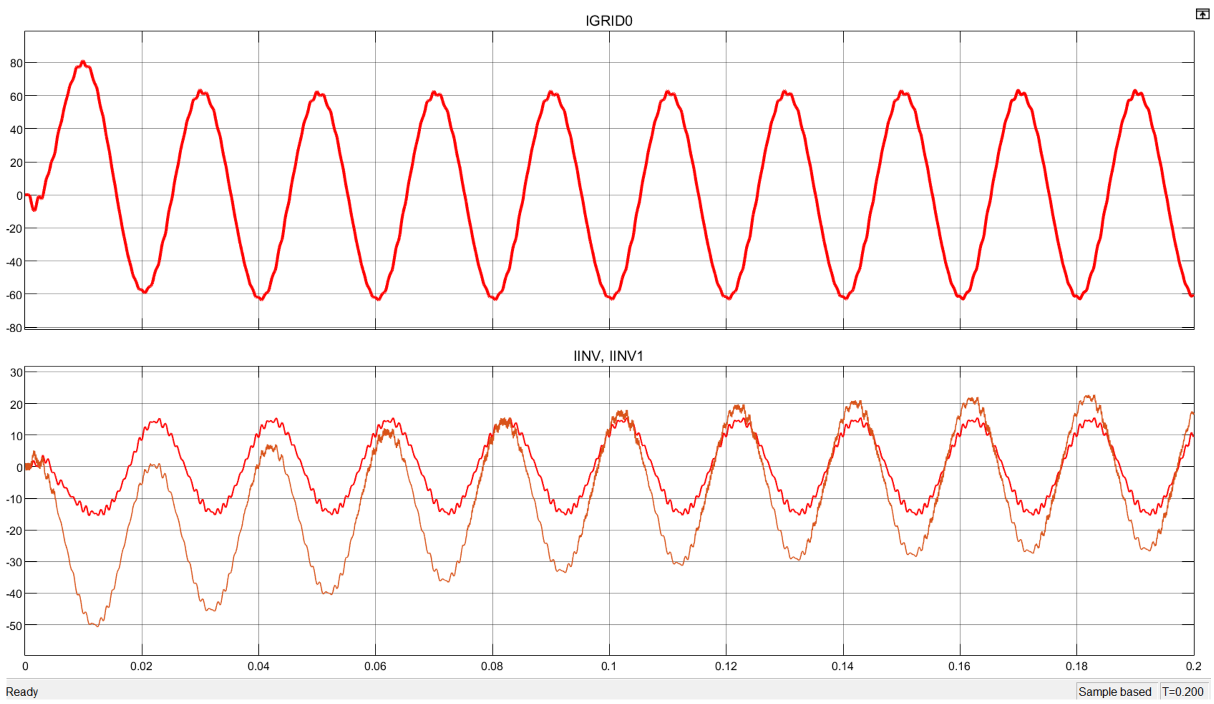

Figure 12. Simulation results of System current and current GTI

In this simulation using a PWM frequency of 5 kHz for each inverter, the system demonstrated fairly good frequency maintenance capability, but failed to maintain the optimal system voltage level. These results, shown in Figures 11 and 12, indicate significant voltage drops and the appearance of harmonic distortion in both current and voltage. This instability occurs because the main inverter unit in the initial simulation is not equipped with an automatic voltage control mode (voltage regulation), unlike conventional electric generator mechanisms that naturally have an Automatic Voltage Regulator (AVR) to regulate voltage.

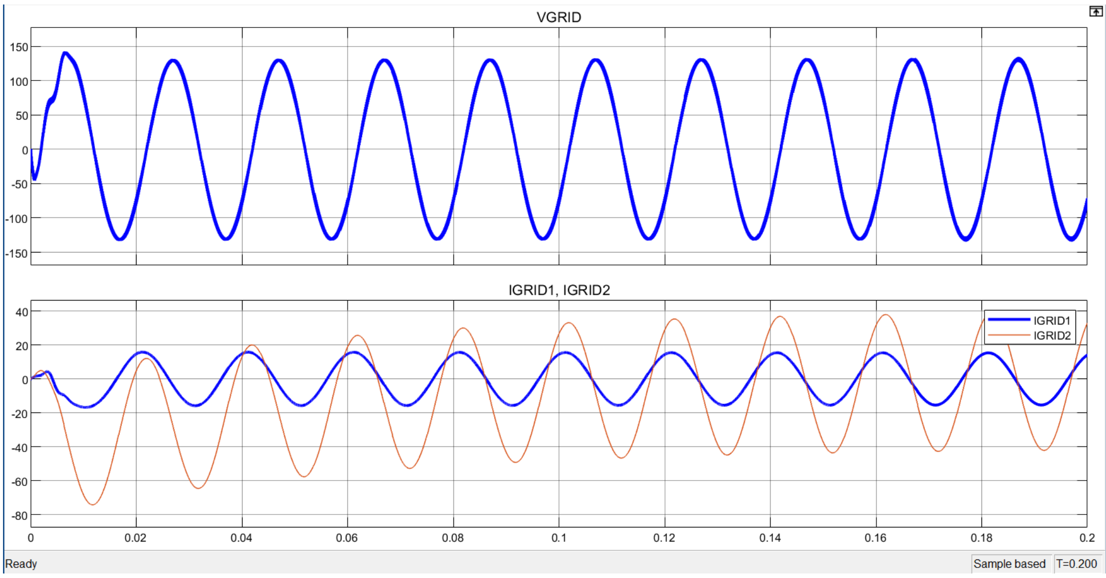

Figure 13. Simulation results of the voltage and current system at GTI frequency 10 kHz

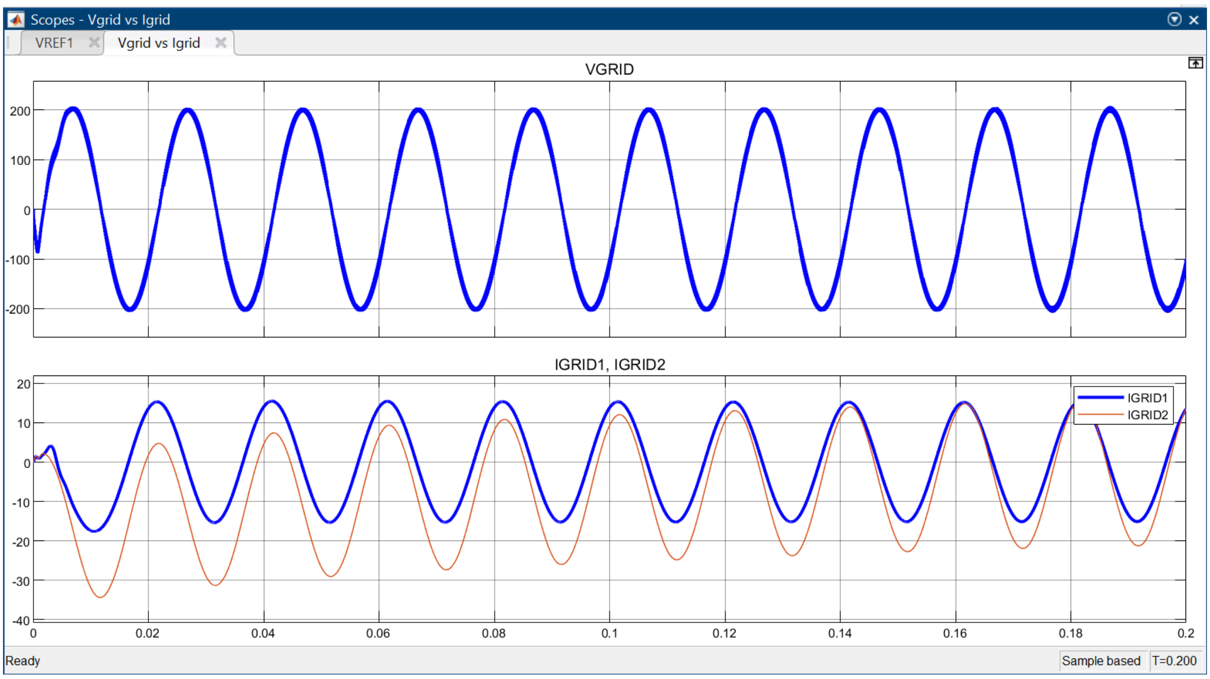

Figure 14. Simulation results of system voltage and current on GTI, master power 10 x GTI power

The simulation involved increasing the PWM frequency of each inverter to 10 kHz as a strategy to improve power quality. Utilizing a higher frequency count for the inverter and GTI facilitates the filtering process for the output voltage and current. The characteristics of the inverter output voltage and current are clearly presented in Figure 13. The next crucial optimization step was carried out by adjusting the power capacity ratio between the master and slave units. By increasing the capacity of the main inverter transformer by 10 times the GTI power (GTI transformer of 1 kVA and Main inverter transformer of 10 kVA), the system shows a very significant performance improvement. The implementation of this 10:1 power ratio proved successful in maintaining a stable system voltage at a value of around 220 V, as confirmed by the simulation results in Figure 14. This finding confirms that in addition to the appropriate PWM modulation technique, the power capacity ratio between the master and slave units is an absolutely necessary design parameter to ensure the stability of the inverter-based microgrid.

3.2 Hardware Implementation and Experimental Analysis

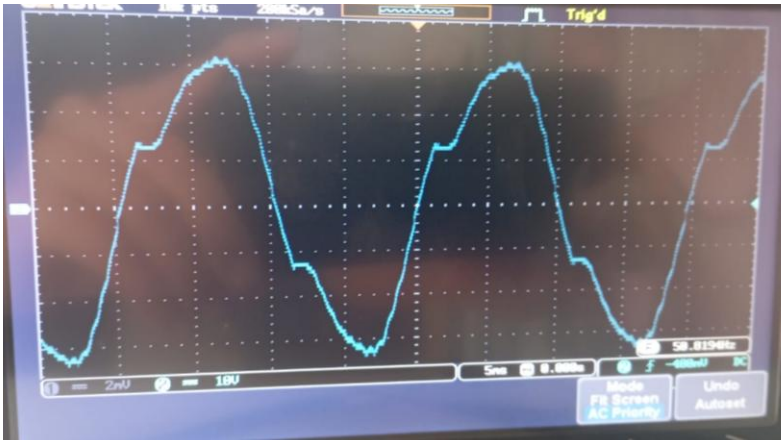

Figure 15. Small single phase generator output with 600 Watt power, 220 Vac and 50 Hz.

Based on the simulation and experimental results, the system configuration used the genset as the primary unit the most significant stability advantages, as seen in Figures 8 and 9, driven by the generator's mechanical inertia in naturally maintaining the frequency and voltage references. On the other hand, the implementation of a microgrid system with an inverter as the primary unit remains feasible, but requires a series of rigorous design optimizations for reliable operation. In Figure 15, the output results using a 600 Watt, 220 Vac and 50 Hz generator are shown and show the presence of voltage harmonics.

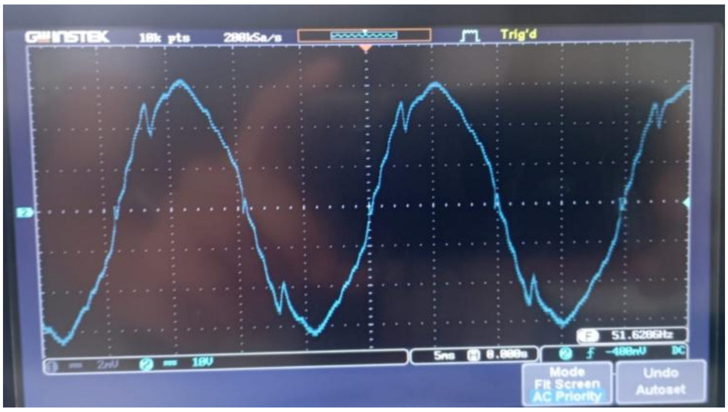

Figure 16. The master generator output is paralleled with the GTI and loaded with an load

The genset as a master is connected in parallel with the GTI as a slave to serve the load (in this study) in the form of a resistive load using an incandescent lamp and produces an output wave in Figure 16.

3.2 IoT Monitoring Analysis

A monitoring system was implemented to assess the dynamic behavior of the microgrid system in real time. This system utilizes an ESP32 microcontroller as the central data processing unit, which is integrated with PZEM-004T sensor modules via a UART serial communication interface, as shown in the hardware assembly in Figure 17. Monitored parameters include voltage, current, active power, accumulated energy, frequency, and power factor, providing a comprehensive overview of the energy conversion efficiency of the off-grid solar power system.

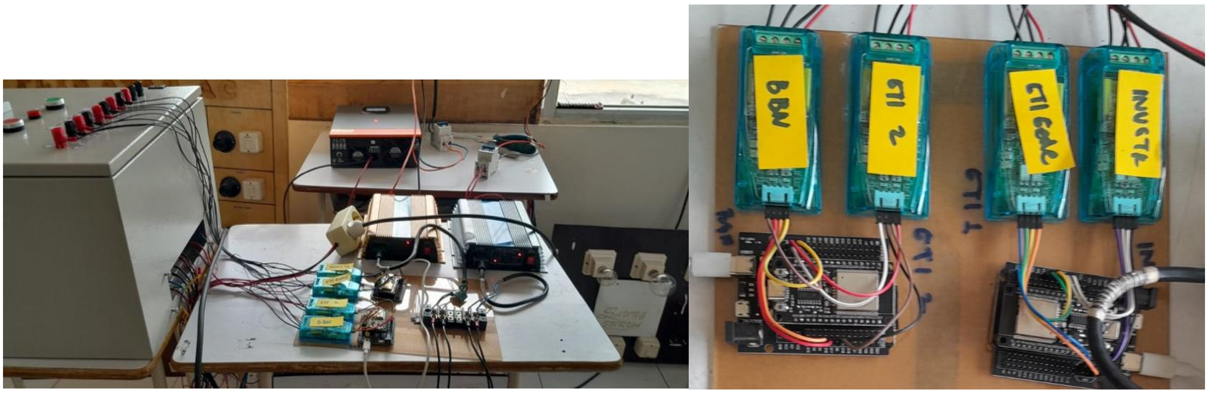

Figure 17. Hardware for data monitoring

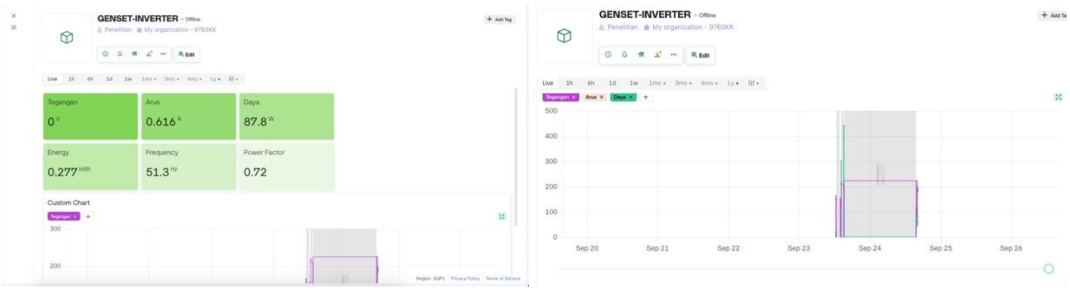

Figure 18. Dashboard of Blynk for data monitoring

Data acquired by the ESP32 is transmitted via an internet connection to the Blynk platform, which serves as the user dashboard interface illustrated in Figure 18. This integration allows for remote monitoring of energy usage trends, with data updates occurring at 5-second intervals. Through this intuitive dashboard, historical energy data can be analyzed to support system optimization processes and validate the extent to which the developed master-slave configuration is able to maintain stable power quality while continuously serving AC loads.

4. CONCLUSION

This study validates the synchronization stability limits of a master-slave microgrid configuration under off-grid conditions. The diesel generator-based master configuration exhibits strong steady-state stability, where at a resistive load of 500 W, the system maintains a consistent output of 212.7 V and 50 Hz with a measured Power Factor (PF) between 0.26 and 0.41; this performance is supported by the generator's mechanical inertia, which provides the necessary stiffness reference for the GTI Phase-Locked Loop (PLL) to effectively phase-lock. In contrast, the inverter-based master configuration consistently fails to maintain synchronization unless a certain power capacity threshold is met, as experimental data confirms that configurations with a master to follower power capacity ratio below 10:1 always trigger reverse power trip protection. IoT-based monitoring reveals that below this ratio, the GTI generates high-frequency switching interference that exceeds the master inverter's control bandwidth, resulting in frequency transient mismatches and loss of synchronization. Therefore, this study establishes a power capacity ratio of 10:1 as a mandatory design parameter for the implementation of off-grid microgrids using an inverter-based master configuration, since achieving grid-equivalent 220 V and 50 Hz power quality depends on maintaining this capacity threshold to suppress disturbances caused by phase locking.

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