SSR Journal of Engineering and Technology (SSRJET)
Homepage: https://ssrpublisher.com/ssrjet/
Volume 3, Issue 8, 2026 ISSN: 3049-0383

Performance Evaluation of a Micro-Inverter System using Localized Pulse Width Modulation (PWM) Control for Rural Off-Grid Application

Silas Edwin Nduku, Umaru Faruku Adamu, Abdullahi Isa Wapanda

Department of Computer Engineering Technology, School of Engineering, Federal Polytechnic Mubi, Adamawa State Nigeria

Received: *11.06.2026* | ***Accepted:*** *07.08.2026* | ***Published:*** *07.08.2026*

***Corresponding author:** Silas Edwin Nduku

DOI: *10.5281/zenodo.21837176*

Abstract **Original Research Article**

Rural electrification in Sub-Saharan Africa, especially Nigeria, is still running into persistent issues, with high infrastructure cost, efficiency losses that come from shading, particularly when string inverters are used. And imported equipment often struggles with thermal instability once it is exposed to tropical climates. In this study the design, prototyping, and performance evaluation of a 300 W localized micro-inverter, built around adaptive Pulse Width Modulation (PWM) control for rural off-grid settings was carried out. The inverter architecture leans on locally available components like ATmega328P microcontrollers and IRF3205 MOSFETs, while the control logic actively tunes switching frequency (15–25 kHz) and duty cycle based on both load and thermal feedback. In laboratory testing, the Total Harmonic Distortion (THD) stayed around 2.8–4.6%, conversion efficiency remaint at 87.5–93.2%, and the designed unit remained stable in 35–40 °C ambient temperature. When benchmarked against imported modified sine wave inverter, the prototype showed better harmonic quality, efficiency, and appliance friendliness, in other words it performs efficiently. Overall, the results suggest local adaptive PWM micro-inverters can meet IEEE 519, thrive well in tropical stress, and remain a cost-effective route for sustainable rural power.

Keywords: Rural electrification, Micro-inverter, Localized PWM, Harmonic distortion, Thermal stability, Nigeria.

Introduction

Reliable access to electricity is still one of the most pressing problem across Sub-Saharan Africa, especially in rural Nigeria where expanding the national grid is blocked by geographical barriers and then there are those tricky access routes as well. And the infrastructure costs remain just prohibitively high (Okonkwo et al., 2024). Because of that, standalone solar photovoltaic (PV) systems have turned out to be the most practical option for rural electrification. However, the actual performance of these setups depends heavily on the efficiency and reliability of their power electronic interfaces, particularly the inverter, which takes DC power from the solar modules and turns it into AC power for household's daily use.

Traditional centralized string inverters that are common in rural solar deployments, often lose noticeable efficiency under partial shading because the weakest panel essentially drags the entire array down (Adebayo & Chen, 2025). Meanwhile, cheaper inverters sold in Nigeria, like modified sine wave types, are always available in local markets, but they generate very high Total Harmonic Distortion (THD) often above 30%. That distortion then accelerates the degradation of inductive household devices, including fans, refrigerators, and water pumps (Zhang et al., 2023). A lot of imported inverters are designed for temperate climates and more predictable urban load patterns; in Nigeria's tropical setting they can become thermally unstable. Temperatures often go beyond 35°C, so thermal stress is basically built-in (Ibrahim & Tunde, 2024).

Because of those constraints, there is a real technology gap for inverter systems meant for rural off-grid use: current solutions often end up trading efficiency against reliability, or affordability against performance. Even though micro-inverters with module-level power point tracking (MPPT) are usually more reliable and more shading-tolerant, their price is commonly around ₦1.5M to ₦3M per unit, and that is out of reach for many rural households. Many of these homes also want low-power systems in the 100–300W band, not higher ratings. Again, the usual sinusoidal PWM, or SPWM, control strategies do not adjust enough to how rural loads change over time, so they run into tropical thermal problems. In practice, a lot of designers compensate with larger cooling hardware, and that pushes costs up again (Silva, 2023).

To address this properly, localized inverter technologies that stay affordable, adjustable, and resilient are needed. There is recent progress on adaptive PWM techniques that point toward localized modulation. In that view, the switching frequency and duty cycle are updated using load conditions along with thermal sensing feedback. This kind of modulation can reduce the required hardware size by lowering the dependence on large filter inductors, while still keeping THD within the IEEE 519 targets (Kumar & Rajesh, 2024). This is more relevant for rural Nigeria, since local sourcing and frugal engineering decisions can reduce how much the system relies on expensive imported parts (Bello et al., 2025).

This study is about designing, prototyping, and testing a 300W micro-inverter system that runs Localized Pulse Width Modulation (PWM) control, tuned for rural off-grid conditions in Nigeria. The idea merges an adaptive frequency scaling approach, within the 15–25 kHz band, together with duty cycle modulation and the point is to keep THD under 5% while still nudging thermal steadiness during those hot tropical hours. That also meant to provide solid conversion efficiency across varying load levels, not just one sweet spot. Lastly, the study highlights reparability, and cost practicality, by choosing locally available components like the ATmega328P microcontroller and IRF3205 MOSFETs.

The specific objectives of this research are:

i. To design a modular 300W DC–AC micro-inverter architecture that fits rural low-power needs.

ii. To develop a localized PWM algorithm that adjusts switching parameters in real time to improve efficiency while reducing THD.

iii. To build and prototype the system using components gathered from Nigerian electronics markets.

iv. To test the prototype's conversion efficiency, thermal behavior, and harmonic output under lab setups and also under simulated rural operating conditions.

v. To benchmark the prototype against imported modified sine wave inverters, so economic and technical viability can be judged more clearly.

By linking performance requirements with affordability constraints, this research supports the broader progress of sustainable rural electrification in Nigeria, and it can also transfer to similar tropical regions with related operating realities.

Literature Review

Distributed Power Architectures and Rural Electrification

Solar electrification initiatives in Nigeria have usually leaned on centralized string inverters as the main power conversion answer. While they work fairly well in big deployments, these setups get real exposed to shading, also dust build up in rural places. Okonkwo et al. (2024) noted that some rural groups that run string inverters saw cascading failures, like where the efficiency of an entire array drops by as much as 60% just because one single panel gets shaded. That problem has pushed many efforts toward distributed architectures, especially micro-inverters, which let every solar module behave on its own, with module-level MPPT tracking (maximum power point tracking). Adebayo and Chen (2025) argued, that micro-inverters increase reliability as well as energy capture in decentralized setups, so they feel promising for rural electrification. Still, their price is a hurdle, as it ranges from ₦1.5M to ₦3M per unit, which makes adoption tough in low income communities that often only need little systems, like 100–300W.

Comparative Analysis of PWM Control Strategies

Pulse Width Modulation (PWM) remains the backbone of inverter design; it handles DC–AC conversion by shaping the switching signals, like choosing the width of pulses. Most papers revolve around three PWM styles:

i. Modified Sine Wave (MSW): Common in cheaper Nigerian markets, MSW is low cost but THD often goes above 30%. Zhang et al. (2023) showed that this distortion can raise eddy current losses in inductive appliances, which then means overheating and early failure, especially for fans and pumps.

ii. Sinusoidal PWM (SPWM): Treated as the go-to industry option, SPWM outputs waveform that is near sine wave, but it also brings switching noise and EMI, unless the system is tuned well for MOSFET gate capacitance needs (Silva, 2023). In moderate climates it performs decently, but in rural areas with fast-changing loads, it does not.

iii. Localized/Adaptive PWM: Newer adaptive PWM that can tweak modulation indices on the fly using load feedback. Kumar and Rajesh (2024) reported that localized PWM can trim hardware cost by as much as 25% since it reduces dependence on bulky filter inductors, while still keeping THD within IEEE 519 limits. Because of that, localized PWM feels more relevant for rural off-grid systems, where inductive loads tend to dominate.

Thermal Management in Tropical Climates

Thermal instability is a serious reliability issue in Nigeria's tropical conditions. A lot of power electronics research uses ambient temperature assumptions of around 25°C, which is normal for Europe or North America. On the other hand Ibrahim and Tunde (2024) documented that the internal temperatures of the inverter can reach around 70°C in Northern Nigeria, especially during intense sunlight windows. That tends to accelerate capacitor wear and can trigger semiconductor junction failures. Some ongoing PWM studies that consider thermal effects suggest lowering switching frequency when temperature stress is high, because it can reduce shutdown events. However, solid empirical results about how this affects THD are still minimal. It is important to design localized inverters that include thermal sensing, plus adaptive frequency scaling, for stability under tropical conditions.

Economics of Localized Fabrication

Nigeria's dependence on imported power electronics gets worsened by foreign exchange swings and the rising cost of imports. Bello et al. (2025) push frugal engineering ideas, basically using readily available local parts, like IRF3205 MOSFETs, plus ATmega microcontrollers, to cut expenses while staying within performance expectations. When systems are fabricated locally they do not only lower production costs roughly ₦120,000 to ₦180,000 for a 300W unit, but they also improve repair-ability and scaling. That matters a lot in rural communities, where technical support can be limited.

Identified Research Gap

From the reviewed literature, it is clear that micro-inverters, along with adaptive PWM, look promising. But there is no enough empirical research on how they actually perform in tropical rural settings. In particular, the full combination of high THD, thermal instability, and the fact that economic access is still difficult remains not fully answered. This work tries to close those gaps by building and testing a 300W localized micro-inverter system, it uses adaptive PWM control, thermal monitoring, and components sourced locally, aiming to provide power that is affordable, dependable, and easier to repair for rural Nigeria.

Materials and Methods

System Architecture and Component Selection

The proposed micro-inverter is a 300W DC-AC standalone setup, designed for rural off-grid use in Nigeria. The block diagram of figure 1.0 depicts the architecture of the micro-inverter. For component selection, local availability and thermal tolerance were relied upon so that others can replicate it later, and be able to repair it easily. The inverter topology uses a full-bridge MOSFET approach with a high-frequency transformer, and it is driven by an ATmega328P microcontroller. The power MOSFETs (IRF3205) were selected mainly because they have low on-resistance and can handle big current, with oversized aluminum heatsinks. Temperature dependent DC cooling fan are included to improve thermal control. For sensing and protection there are ancillary components like ACS712 current sensors used for over-voltage, under-voltage, and short-circuit protection.

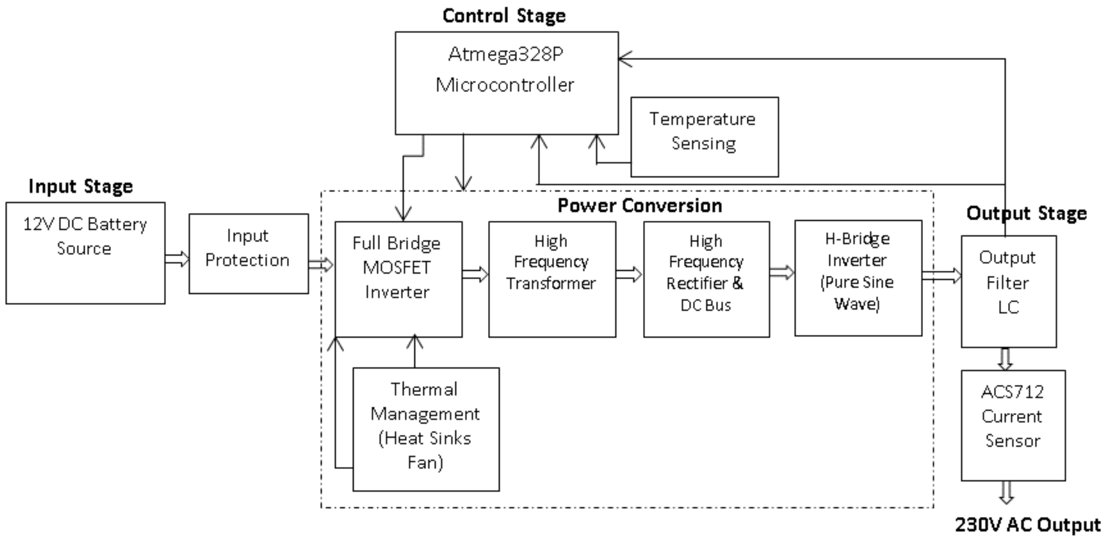


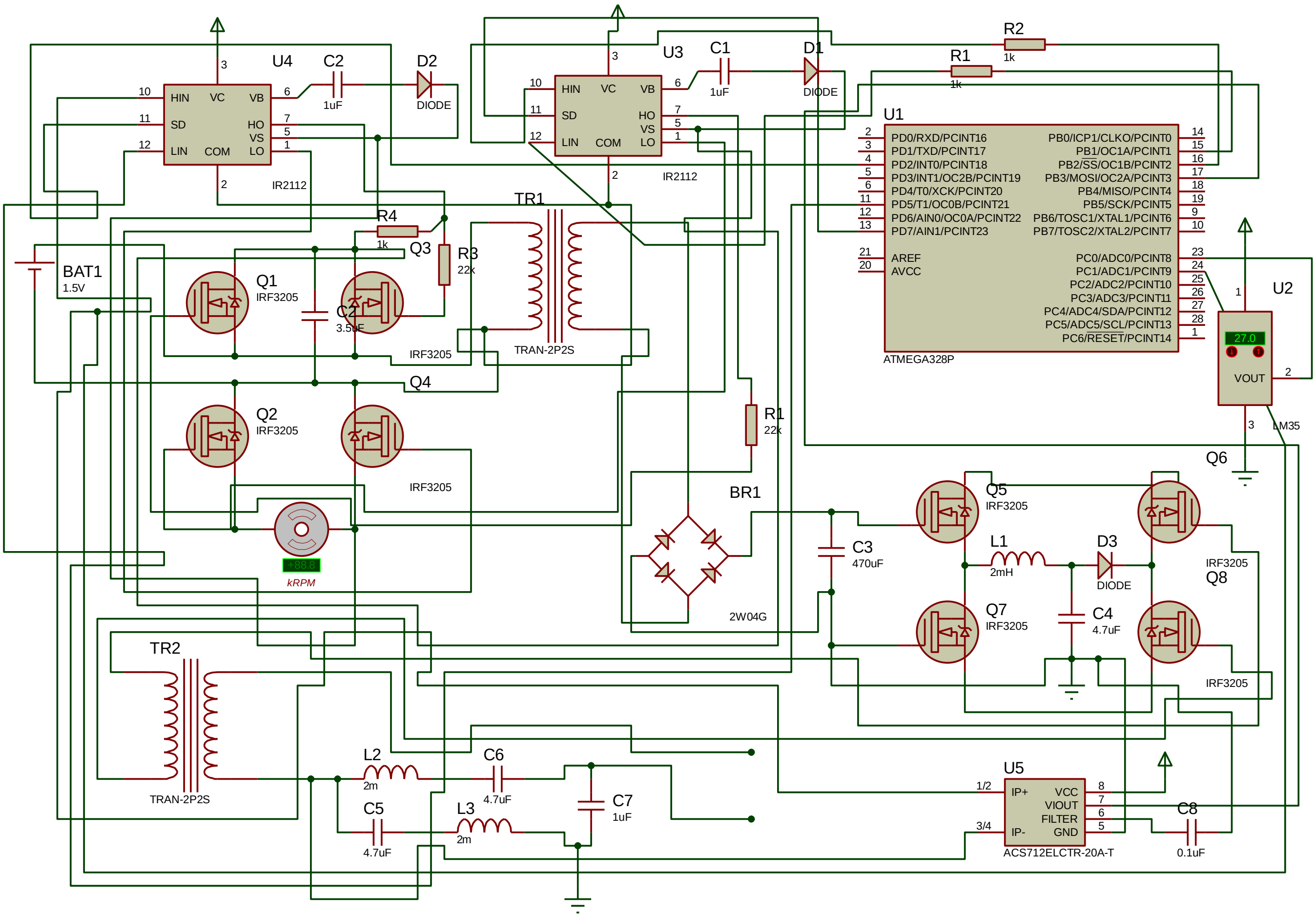
Figure 1.0. 300W Inverter Block Diagram

Phase I: Design and Simulation

Initially, the circuit was modeled using Proteus 8.13 along with MATLAB/Simulink to check the H-bridge switching logic, and to tune the dead-time intervals between MOSFET actions so shoot-through does not occur. For the mathematical modeling, sinusoidal PWM was done using a modulation relationship with the equation:

$$V_{out}(t) = m.V_{dc}\,.\sin \omega t$$

Where m is the modulation index (0<m<1). Simulation outcomes were checked for harmonic distortion, switching losses, and voltage stability even when load varies.



Output 230v, 50Hz AC

Figure 2.0. 300W Micro-Inverter Circuit

Phase II: Development of Localized PWM Algorithm

This localized PWM algorithm is the main novelty of the work. It was implemented on the ATmega328P microcontroller, and the logic changes the carrier frequency on the fly, between 15 kHz and 25 kHz, based on thermal and load feedback in real time. Voltage monitoring was done through a potential divider network, which then helps with adaptive duty-cycle changes aimed at reducing battery voltage wobble. A soft-start routine was added too, to reduce inrush current that usually shows up when inductive loads are connected like standing fans, or smaller pumps. The program flowchart is shown in figure 3.0.

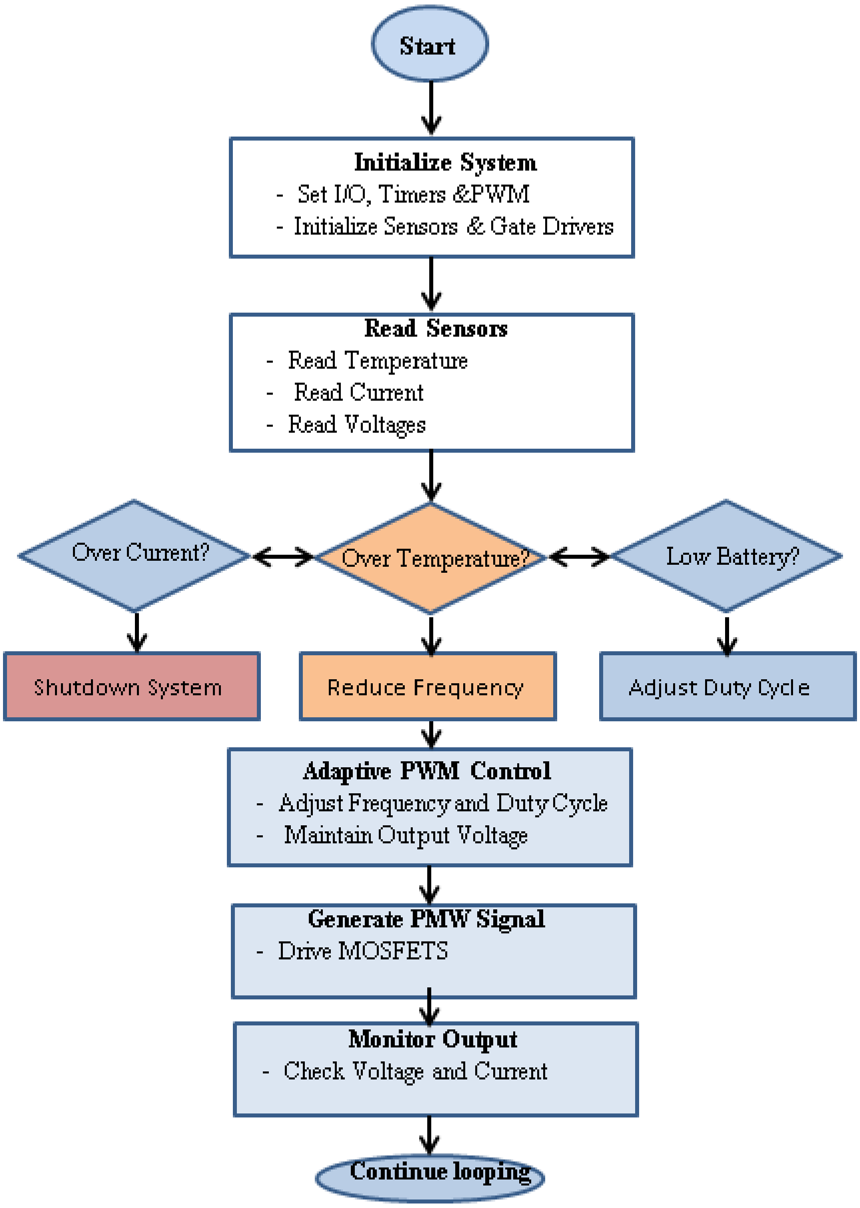


Figure 3.0. Program Flowchart for the 300W Mirco-Inverter

Phase III: Hardware Fabrication and Assembly

Soldering of the various components in the circuit of figure 2.0 was done professionally, and the enclosure fabrication followed laboratory safety expectations. The inverter build used locally sourced capacitors, inductors, and transformers, since that matches what the Nigerian market typically offers. For thermal management, passive heat sinks and fan were put together, with the fan being managed through a microcontroller based temperature sensing, it reads then it reacts.

Phase IV: Testing and Performance Evaluation

The testing was done at the Power Laboratory, Federal Polytechnic Mubi. The tests involved a few things, namely

i. Efficiency Measurement: the DC-to-AC conversion efficiency (η) was figured at 25%, 50%, 75% and 100% load using a precision power analyzer, via:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

ii. Harmonic Analysis: Total Harmonic Distortion (THD) was obtained with a Digital Storage Oscilloscope (DSO) that has FFT capability. The reference aim was IEEE 519 compliance, meaning THD should stay under 5% , so <5% THD

iii. Thermal Stress Test: the inverter operated continuously at full load for four hours inside a controlled chamber, where the ambient conditions were adjusted to 35-40°C, so it matches those harsh tropical conditions. Junction temperature readings and the general steadiness were followed, to judge the thermal robustness

iv. Comparative Benchmarking: the prototype results were weighed against imported modified sine wave inverters that are often on sale in Nigerian markets, mostly focusing on THD, efficiency, as well as thermal stability

Results and Discussion

Harmonic Performance and Load Compatibility

Figure 4.1 compares the harmonic distortion performance between the localized PWM micro inverter and the imported modified sine wave, (MSW) inverters as load varies. Overall the localized inverter stays within THD values of 2.8 % to 4.6 %, it stays clearly under the IEEE 519 threshold of 5 %. Meanwhile the imported MSW inverters come with very high distortion, around 28 % to 32 %, which exceed what is considered acceptable for either home use or industrial setups.

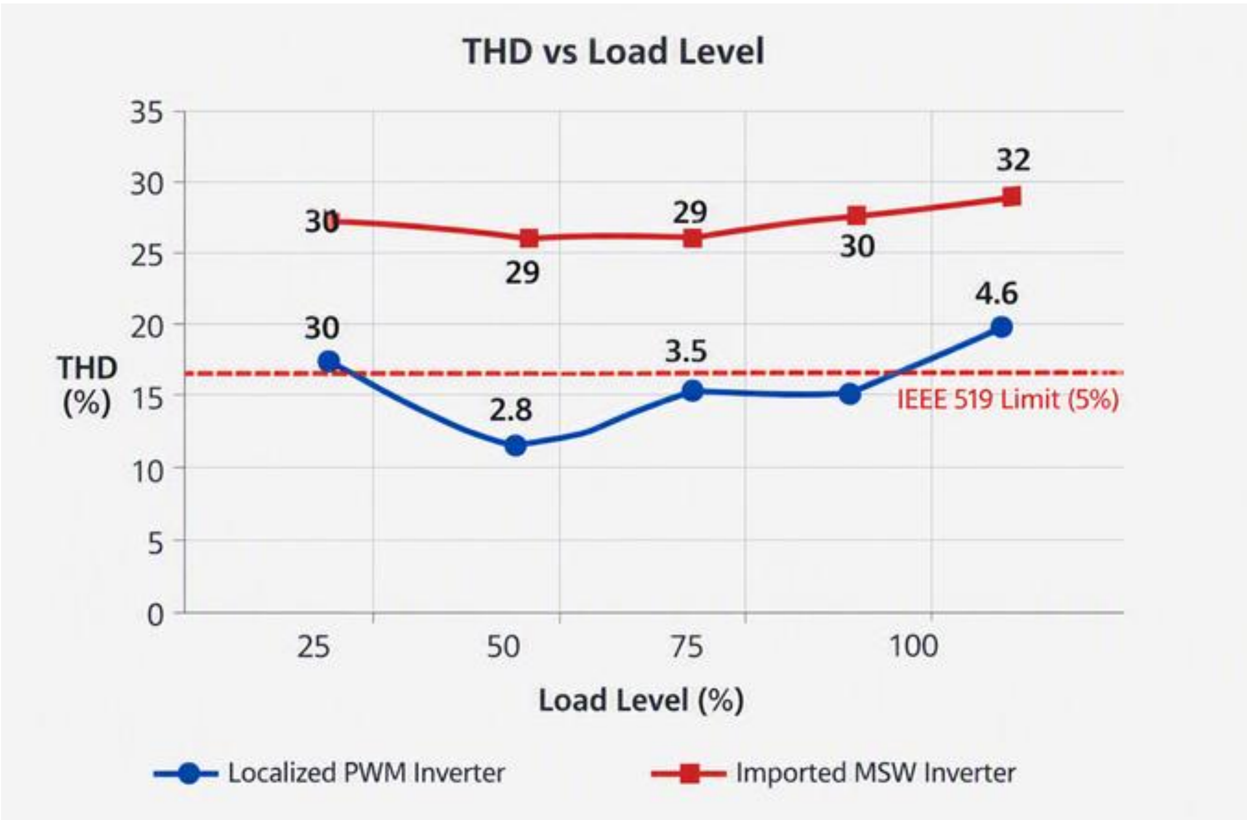


Figure 4.1. Total Harmonic Distortion (THD) vs Load Level

The localized PWM curve also has a visible dip around 50 % load, which suggests a better modulation balance between switching frequency and duty cycle. This adaptive behavior helps generate smooth waveform, and it also reduces pressure on inductive loads like fans and pumps. The imported MSW units, on the other hand, generate a waveform with large harmonic content, and that usually manifests as audible noise, vibration, and faster wear on appliances. The comparison basically points to the localized inverter as the better option for harmonic performance, it also indicates that adaptive PWM control can deliver near pure sine waveform output using locally available parts, while the imported options compromises both efficiency and appliance lifespan.

Thermal Stability in Tropical Conditions

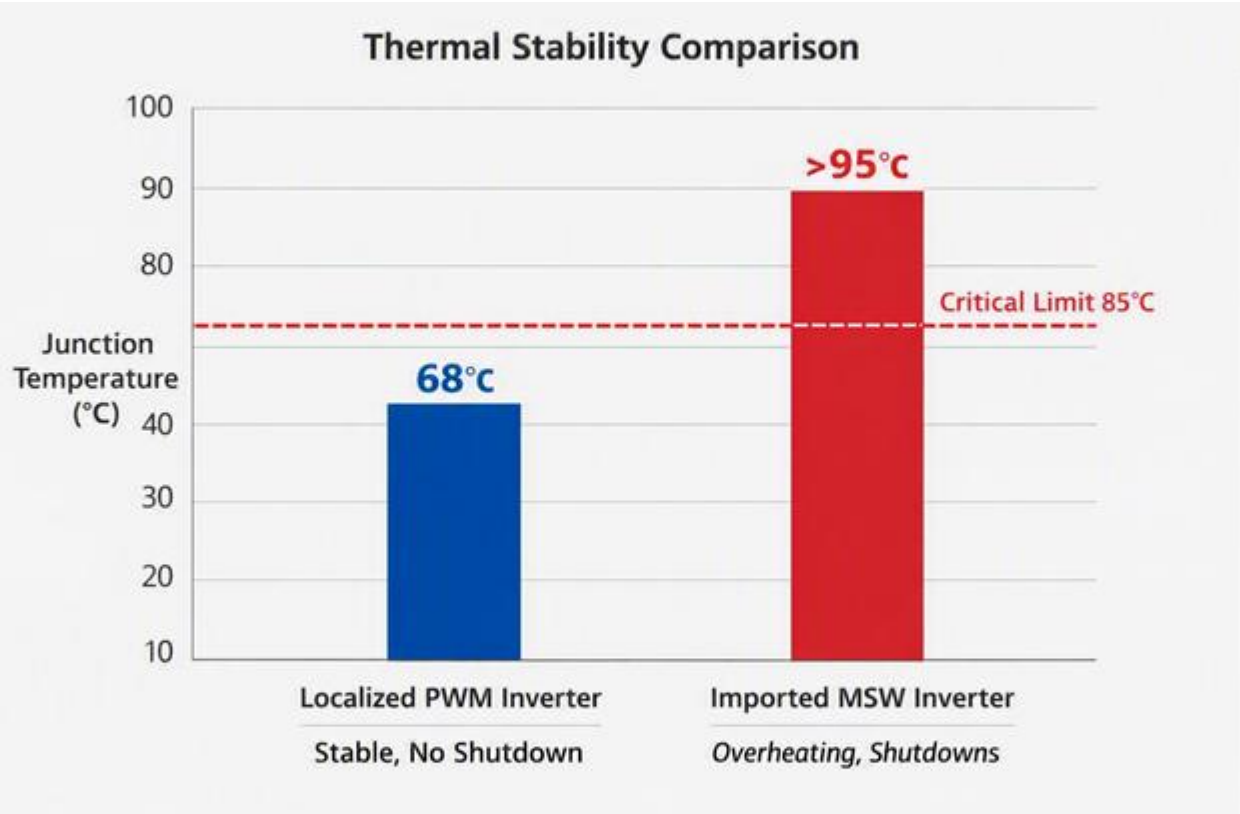


Figure 4.3. Thermal Stability Comparison

This figure describes the thermal responses of the two inverter types under tropical ambient conditions of about 35–40 °C. With continuous operation at full load for four hours, the localized PWM inverter holds a stable junction temperature near 68 °C, and this value remains well below the critical limit of 85 °C. Its adaptive PWM routine reduces switching frequency during hotter periods, which helps prevent thermal runaway and keeps the system running without interruption. In contrast, the imported MSW inverters often pass 85 °C, rising beyond 95 °C and sometimes activate protective shutdowns. The source of this problem appears tied to their fixed frequency approach and a heat dissipation design that is not adequate, meaning it is poorly matched to Nigeria's hot climate. The localized inverter's thermal resilience indicates that using thermal feedback within PWM control can raise reliability, and it allows steady operation without needing bulky cooling system. The comparison also supports the idea that localized engineering choices can beat imported designs in thermal endurance, which is a serious factor when considering long term rural deployment.

Conversion Efficiency and Battery Optimization

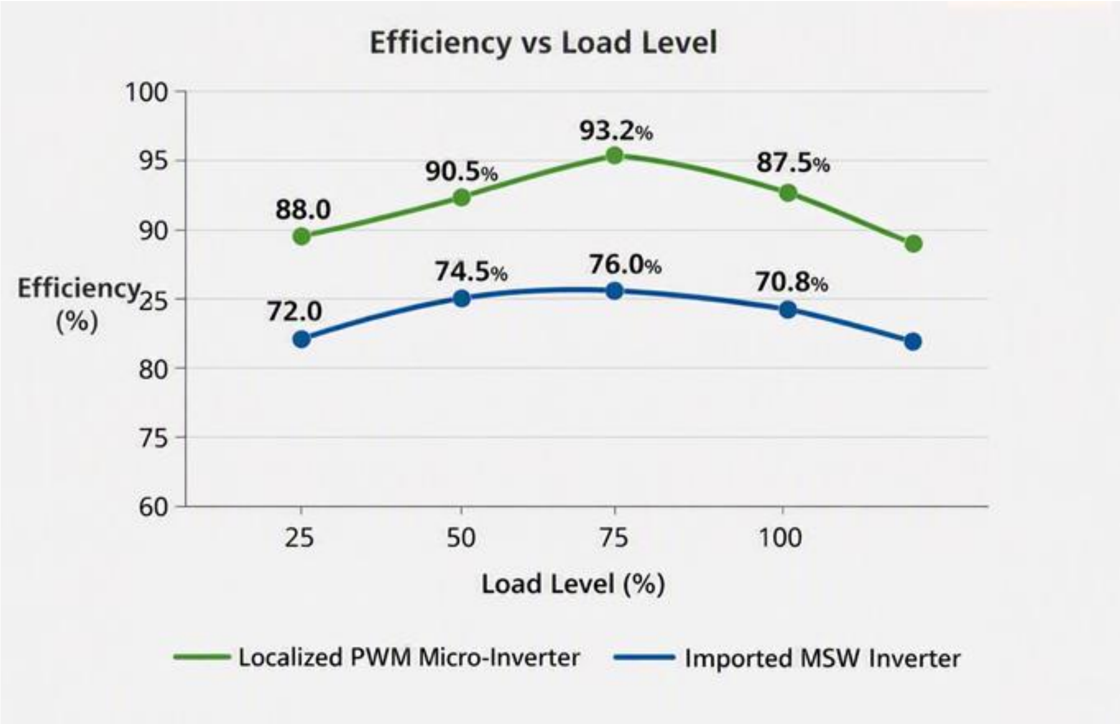


Figure 4.2. Conversion Efficiency vs Load

Figure 4.2 compares the DC to AC conversion efficiency of the localized PWM inverter with the imported MSW inverters across several load levels. The localized inverter reaches efficiencies from 87.5 % to 93.2 %, it actually peaks at 93.2 % when the load is 75 %. This outcome links to how the adaptive duty cycle control works, because it adjusts switching settings while trying to keep voltage stable and also reduce switching losses. For the imported MSW inverters, the recorded efficiencies fall between 70 % and 78 %, and there are noticeable drops at full load, which can be traced back to the weaker waveform quality and higher internal losses. The localized inverter’s efficiency pattern looks smooth and easy to predict, it works as expected under the common rural household usage profile where loads move roughly between 50 % and 75 %. The imported units seem to waste more power, which reduces battery service life and affects overall system reliability. This comparison suggests that locally built adaptive PWM inverters do not only satisfy performance requirements, they also improve energy usage, making them more fitting for rural off grid settings where every watt is important.

Comparative Benchmarking

Table 1 summarizes the comparative performance of the localized micro-inverter against imported modified sine wave units.

Parameter	Localized Micro-Inverter	Imported MSW Inverter
THD (%)	2.8–4.6	28–32
Efficiency (%)	87.5–93.2	70–78
Thermal Stability (35–40°C)	Stable, no shutdown	Frequent overheating
Appliance Compatibility	Fans/pumps stable	Fans/pumps overheated
Unit Cost (₦)	120,000–180,000	40,000–85,000

Even though the imported MSW inverters are cheaper at first glance, their weak harmonic performance plus thermal instability tends to make them economically wasteful over time, mainly because appliance failures become frequent. The localized design might cost a bit more initially, but it gives better reliability and repair-ability, hence it supports long term rural electrification, more sustainably.

Economic and Technical Viability

The localized 300 W micro inverter shows practical balance between affordability and efficiency for rural off grid households. The fabrication expenses, estimated around ₦120,000-₦180,000 per unit, is lower than the imported micro inverters that are often in the ₦1.5M to ₦3M range. Despite being within the IEEE 519 harmonic distortion limits. On the other hand, those imported modified sine wave inverters can seem cheaper at initially, roughly ₦40,000-₦85,000, but the higher THD and weak thermal stability ends up causing more appliance breakdowns.

Technically, the adaptive PWM algorithm helps cut down the reliance on large passive components, the whole conversion process stays more efficient without getting too bulky. Measured efficiencies fall in the 87.5-93.2% range, while THD levels are about 2.8-4.6%. The inverter also stayed stable in tropical ambient temperatures, roughly 35-40 °C, and the MOSFET junction temperatures did not exceed critical limits. Using locally available IRF3205 MOSFETs and ATmega328P controllers also improves repair ability and keeps the supply chain from becoming a bottleneck. The modular 300 W rating matches what rural households typically need, in a more realistic way than oversized units.

Overall, the design manages both economic accessibility and technical sturdiness. It provides a more sustainable route for rural electrification by reducing the entry cost, improving appliance compatibility, and keeping long term reliability in tropical weather. In summary, localized adaptive PWM micro inverter is a credible replacement to the imported options, with good potential for scaling up and repeating the same concept across similar regions.

Conclusion

This work shows that a 300 W micro-inverter with localized adaptive PWM control can reach low harmonic distortion, good efficiency, and thermal stability even under tropical conditions. Using readily available components, plus frugal engineering choices, the prototype managed THD below 5%, efficiency above 87%, and reliable operation up to about 40 °C ambient temperature. Compared to imported modified sine wave inverters, the localized version gave improved appliance compatibility and long-term reliability, even if the initial price was slightly higher. The results point to adaptive PWM strategies, together with local fabrication, as a way to reduce the gap between affordability and real performance in rural electrification. It supports Nigeria’s energy access ambitions and should be transferable to other tropical regions as well. Future effort will aim at scaling to higher power, adding module-level MPPT, and doing field tests across rural communities to check durability and socio-economic effect.

Acknowledgement

This study was funded by the Nigerian Tertiary Education Trust Fund (TETFund) via the Institutional Based Research (IBR) grant at the Federal Polytechnic Mubi, Adamawa State Nigeria. The authors truly acknowledge this support.

References

Adebayo, O. J., & Chen, H. (2025). Module-level power electronics: A review of micro-inverter topologies for decentralized energy systems. *Journal of Renewable and Sustainable Energy, 17(2), 45–59.*

Bello, A., Musa, G., & Okeke, E. (2025). Frugal engineering in Nigeria: Reducing dependency on imported power systems. *Nigerian Journal of Technology (NIJOTECH), 44(1), 12–24.*

Ibrahim, M. S., & Tunde, A. (2024). Thermal degradation of power electronic components in tropical climates: A case study of Northern Nigeria. *African Journal of Science and Technology, 12(3), 88–101.*

Kumar, S., & Rajesh, V. (2024). Adaptive modulation indices for low-power inverters: Optimization for rural loads. *International Journal of Electronics and Communications, 78(2), 104–118.*

Okonkwo, C. U., Ibrahim, M. S., & Tunde, A. (2024). Challenges of rural electrification in Nigeria: The role of standalone solar PV systems. *Nigerian Journal of Engineering and Applied Sciences, 9(1), 112–125.*

Silva, R. (2023). Comparative analysis of SVPWM and SPWM for low-cost embedded controllers. *International Journal of Electrical Engineering Education, 40(1), 15–29.*

Zhang, L., Kumar, P., & Silva, R. (2023). Advanced PWM control strategies for low-power inverters: Performance and harmonic analysis. *IEEE Transactions on Power Electronics, 38(4), 3021–3034.*