Diligence analysis for micro grid systems in islanded mode of operation with optimal switching control of converter

Pritha Gupta[1], Mahesh Singh[2], Shimpy Ralhan[3], Mangal Singh[4]
[1]Department of Electrical & Electronics Engineering, Shri Shankaracharya Technical Campus, Bhilai, India
[2]Department of Robotics and Automation Engineering, Symbiosis Institute of Technology, Pune Campus, Symbiosis International (Deemed University), Pune, India
[3]Department of Electrical & Electronics Engineering, Shri Shankaracharya Technical Campus, Bhilai, India
[4]Department of E&TC, Symbiosis Institute of Technology, Pune Campus, Symbiosis International (Deemed University), Pune, India

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ABSTRACT

To operate a microgrid system in islanded mode, it is essential to analyze the economic feasibility and performance of the system. The proposed system integrates two or more renewable energy sources, providing a promising solution for meeting energy needs sustainably. Conducting a techno-economic analysis of such microgrid systems is critical to maximizing the efficient utilization of renewable energy sources. The simulations for these microgrid systems are performed using HOMER Pro software, where various economic parameters—such as cost of energy (COE), electricity production, net present cost (NPC), carbon emissions, fuel consumption, and payback period—are evaluated for the proposed systems. Additionally, the system's performance is analyzed using PSIM software, which incorporates optimal switching control. The results are further validated using a prototype hardware setup. The findings indicate that the PV/hydro system with NPC: 705,658 Rs and payback period: 9.65 years is the most suitable option for meeting the electricity demand in rural areas. Also, through optimal switching control applied to the micro grid converter the output voltage achieved is seven levels and harmonic distortion is 3.7% for voltage and 1.7% for the current.

Corresponding Author:

Pritha Gupta
Department of Electrical & Electronics Engineering, Shri Shankaracharya Technical Campus
Bhilai 491001, India
Email: prithagupta.25@gmail.com

1. INTRODUCTION

The growth of micro grid systems, especially in rural and off-grid areas, has been fueled by the global need for dependable and sustainable energy solutions [1], [2]. By combining several renewable energy sources, including hydro, solar and wind, microgrids provide a decentralized method of energy production and delivery that guarantees a reliable and sustainable power supply. Among their operational modes, islanded operation is particularly significant, as it enables microgrids to function independently from the main grid, offering resilience in areas with limited or no grid connectivity [3].

This study focuses on the techno-economic analysis and performance evaluation of hybrid renewable energy-based micro grid systems operating in islanded mode. By integrating two or more renewable energy sources, these systems promise a sustainable solution for meeting rural energy demands while minimizing environmental impacts [4], [5]. Advanced simulation tools, including HOMER Pro and PSIM, are employed to assess the economic viability and operational performance of proposed systems. Moreover, hardware validation provides practical insights into system feasibility. The findings highlight the potential of hybrid configurations, particularly the c system, in addressing rural electrification challenges with optimal efficiency and cost-effectiveness.

2. FEASIBILITY ANALYSIS OF MICROGRID SYSTEM (CASE STUDY)

The rising demand for electricity in India, driven by factors like industrial development, agriculture, and living standards, has left many rural areas without adequate energy access. Tendua, a village in the Balrampur district of Chhattisgarh, is one such location. This study aims to address its energy needs through a simulation model utilizing PV/hydro and PV/diesel microgrid configurations, developed using HOMER Pro software. The research includes an economic feasibility analysis of these systems to determine their potential for sustainable rural electrification [6].

2.1. Site and resource assessment

A comprehensive survey was conducted in Tendua, accounting for load requirements and available natural resources such as solar radiation, hydro flow from the Kanhar River, and wind data sourced from NASA. The village has 100 houses with a total population of 500, requiring an estimated load of 10 kW compared to the existing 2 kW capacity. Monthly solar radiation data showed an average of 5.98 kWh/m²/day, with seasonal variations. This data informed the development of hybrid energy systems combining solar and hydro resources.

2.2. Proposed microgrid configuration

The study simulated and analyzed two hybrid microgrid configurations to evaluate their performance and feasibility. These configurations were optimized in HOMER Pro to ensure they met the load demand efficiently while minimizing costs [7], [8]. Component details, including installation and maintenance costs, were specified for accurate simulation and analysis. Figures 1 and 2 represents the simulation of proposed micro grid systems.

2.2.1. System 01: PV-hydro-battery-converter configuration

This configuration consists of the PV system hybrid with the hydro generator. The major key components used for developing the energy model are:

- Photovoltaic (PV) panels: The system incorporates 10 kW of PV panels, leveraging solar energy as a renewable power source to supply electricity.
- Hydro generator: A 98 kW hydro generator forms the backbone of this configuration, utilizing a consistent water flow to provide a reliable and sustainable energy supply.
- Battery storage: The system uses 52 strings of lead-acid batteries to store excess energy generated during periods of high production and supply power during demand peaks or low production periods. Lead-acid batteries are chosen for their cost-effectiveness and reliability.
- Converter: A 3 kW converter is included in the system to manage the conversion of DC power generated by the PV panels and batteries into AC power for consumer use. This ensures compatibility with the electrical requirements of the load.

2.2.2. System 02: PV-diesel-battery-converter configuration

This configuration mirrors System 01 in design but replaces the hydro generator with a 98 kW diesel generator. The key components are as follows:

- Photovoltaic (PV) panels: Retains the 10 kW solar PV system, providing a renewable energy component to reduce reliance on conventional fuels.
- Diesel generator: Substitutes the hydro generator with a 98 kW diesel generator, introducing a non-renewable energy source for power generation. This setup is typically employed in scenarios where hydro resources are unavailable or inconsistent.
- Battery storage: Similarly integrates 52 strings of lead-acid batteries for energy storage and load balancing.
- Converter: A 3 kW converter is also included to handle power conversion tasks.

2.2.3. Comparison and purpose of simulations

The primary objective of simulating these configurations is to:

- Assess the techno-economic feasibility of the two systems.
- Compare their energy generation capabilities, fuel consumption, emissions, and overall efficiency.
- Analyze their suitability for rural applications, taking into account factors such as resource availability, operational costs, and environmental impact.

By incorporating both renewable (solar, hydro) and non-renewable (diesel) resources, the study aims to identify the most sustainable and cost-effective configuration for off-grid or rural areas with varying resource accessibility.

The hybrid microgrid configurations were optimized using HOMER Pro, a sophisticated tool for modeling and analyzing hybrid energy systems, ensuring they met electrical load demands efficiently while minimizing costs. The optimization process focused on fulfilling the load demand consistently, even during peak periods, while minimizing the levelized cost of energy (LCOE), a crucial metric that captures the average cost of electricity over the system's lifetime. Detailed cost analyses included capital costs for installation, operation and maintenance (O&M) costs for periodic servicing, replacement costs for components like batteries and converters, and fuel costs for the diesel generator in System 02. The technical and economic details of each component, such as efficiency, lifetime, and operational characteristics, were specified for accurate simulation. Resource availability, including solar irradiation, water flow for the hydro generator, and diesel supply, was incorporated to evaluate the systems' feasibility under different conditions. Environmental considerations were also a significant part of the analysis, aiming to minimize greenhouse gas emissions, particularly from the diesel generator in System 02. Multiple scenarios and sensitivity analyses were conducted to assess the robustness of each system design under varying economic and environmental factors. The optimization provided insights into the performance, cost-effectiveness, and sustainability of the two configurations, emphasizing the role of renewable resources like PV and hydro in reducing costs and emissions. It also highlighted the trade-offs of using a diesel generator in areas without consistent hydro resources, demonstrating the feasibility of tailored hybrid systems for rural electrification.

The performance analysis revealed that the PV/hydro system (MG-01) outperformed the PV/diesel system (MG-02) in terms of annual energy generation, producing 17,900 kWh/year compared to 16,700 kWh/year from MG-02. This difference underscores the advantage of integrating a hydro generator, which can harness a consistent renewable energy source to enhance overall system output. Both systems demonstrated high reliability, with minimal unmet load and negligible capacity shortages, ensuring they effectively met the 10 kW load demand even during peak consumption periods. Additionally, the analysis identified that MG-01 exhibited a slightly higher level of excess electricity compared to MG-02. This surplus energy indicates that MG-01 has a greater ability to scale up to meet future increases in energy demand, making it a more adaptable option for growing energy needs in rural or off-grid settings. The scalability of MG-01 could also provide opportunities for additional applications, such as integrating electric vehicle charging or powering new community facilities. This performance metric highlights the potential long-term benefits of leveraging a renewable energy-based hybrid system like PV/hydro, not only in meeting current demands but also in accommodating future expansion with minimal additional investment.

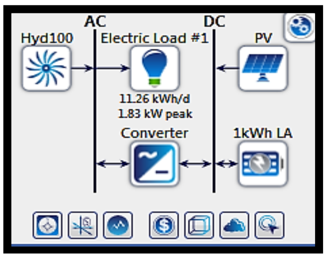


Figure 1. Energy model of microgrid-01 (PV/hydro) systems

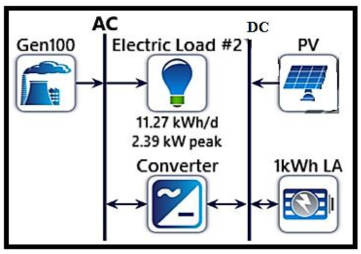


Figure 2. Energy model of microgrid-02 (PV/diesel) systems

2.3. Economic analysis

The cost analysis included metrics like capital expenditure (CAPEX), operating expenditure (OPEX), and net present cost (NPC). Table 1 shows the PV/hydro (MG-01) and PV/diesel microgrid (MG-02). The PV/hydro system (MG-01) required higher initial investment costs compared to the PV/diesel system (MG-02), primarily due to the capital-intensive nature of hydro generator installation and associated infrastructure. However, over the system's lifespan, MG-01 proved to be significantly more sustainable and cost-effective. A key factor contributing to this long-term economic advantage is the zero fuel consumption characteristic of the hydro generator, which eliminates the recurring expense associated with diesel procurement and transportation in MG-02. In addition to economic savings, MG-01's reliance on renewable energy sources (solar and hydro) ensured zero greenhouse gas emissions during operation, making it an environmentally superior alternative. This aligns with global efforts to reduce carbon footprints and transition toward cleaner energy systems. By contrast, MG-02's dependence on a diesel generator led to continuous fuel costs and emissions, making it less favorable from both economic and environmental perspectives.

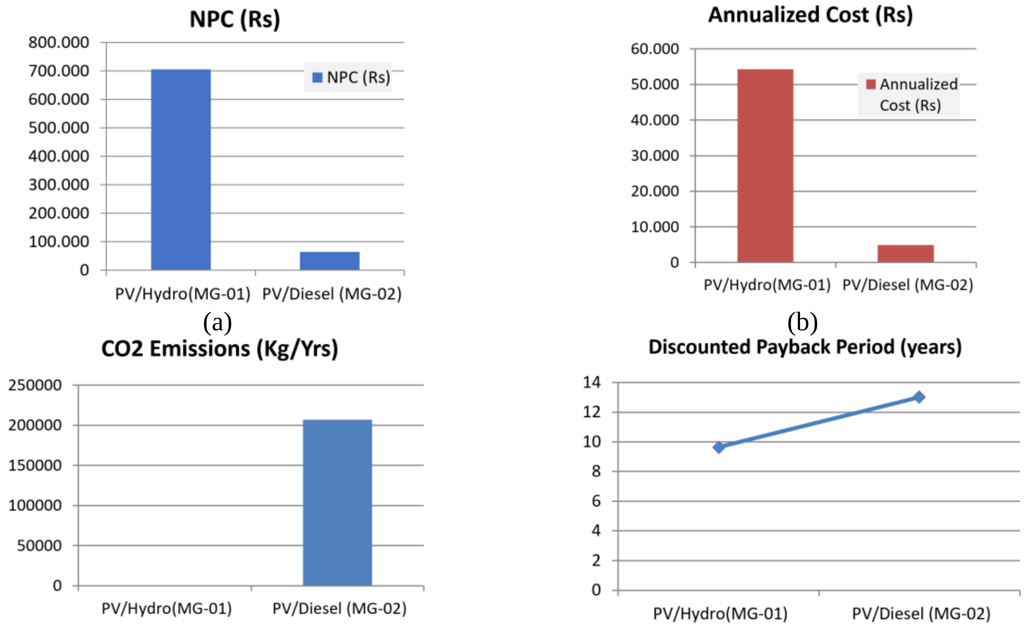
Figure 3 presents a comparative analysis of the key economic and environmental metrics for the two hybrid microgrid configurations: PV/hydro system (MG-01) and PV/diesel system (MG-02). The metrics in Table 1 include (a) net present cost (NPC), (b) annualized cost, (c) CO2 emissions, and (d) discounted payback period, providing a comprehensive evaluation of their performance. The PV/hydro system (MG-01) demonstrated superior economic feasibility with a discounted payback period of 9.20 years, significantly shorter than the 13-year payback period of the PV/diesel system (MG-02). Although MG-01 required higher upfront capital costs due to the hydro generator's installation, its reduced operational expenses, zero fuel costs, and absence of emissions enhanced its long-term financial attractiveness. The Internal Rate of Return (IRR) for MG-01 was calculated at 13.8%, a robust figure that further supports its recommendation for implementation. The higher IRR reflects the system's ability to generate better returns on investment over its lifecycle compared to MG-02. In contrast, MG-02's reliance on a diesel generator contributed to recurring fuel costs and substantial CO2 emissions, making it less environmentally sustainable and economically viable in the long run. Overall, the analysis in Figure 3 highlights the PV/hydro system's economic and environmental advantages, reinforcing its suitability for sustainable rural electrification and long-term energy planning.

2.4. Comparative insights

The economic and environmental viability of a standalone PV system, PV/hydro microgrid, and PV/diesel microgrid were evaluated. With a levelized cost of energy (LCOE) of 12.52/kWh as compared to 24.39/kWh for the PV/diesel system, the PV/hydro system was found to be the most balanced choice. Additionally, the PV/hydro system achieved better production efficiency without reliance on fossil fuels, making it a sustainable choice for Tendua. Both systems efficiently met the demand with minimal excess electricity and unmet load.MG-01 showed lower lifecycle costs and shorter payback periods, despite higher initial investment.MG-01 produced no emissions, aligning with global sustainability goals.

Table 1. PV/hydro (MG-01) and PV/diesel micro grid (MG-02)

PV/hydro micro grid (MG-01)		PV/diesel micro grid (MG-02)	
NPC	705,658 Rs	NPC	63,850 Rs
Annualized cost	54,298 Rs	Annualized cost	4,939 Rs
Discounted payback period	9.65 years	Discounted payback period	13 years
CO2 emissions	Zero	CO2 emissions	207,076 kg/year



(c) (d)

Figure 3. Comparison of key economic and environmental metrics for the two hybrid microgrid configurations: (a) net present cost (NPC), (b) annualized cost, (c) CO2 emission, and (d) discounted payback period for MG-01 & MG-02

3. PERFORMANCE ANALYSIS (PSIM SIMULATION)

To guarantee the dependability of the entire system, the suggested converter is especially made for microgrid systems [9]-[11]. Through the use of an auxiliary circuit and the proposed architecture, the standard inverter's levels are extended, resulting in a seven-level output voltage and a considerable drop in total harmonic distortion (THD) [12]. By increasing the multilevel inverter’s level, THD can be further reduced. Voltage levels are increased and THD is further reduced when a multilevel inverter is incorporated into a hybrid system [13], [14]. By using multilevel inverters, this method enhances the voltage gain and performance profile of traditional inverters. Furthermore, THD is successfully decreased by expanding the multilevel inverter system's level count [15], [16]. Figure 4 illustrates how PSIM software was used to simulate this suggested system. The suggested converter's ideal switching order for micro grid systems is shown in Table 2. Additionally, the voltage level is brought close to sinusoidal with the aid of an auxiliary circuit and appropriate switching sequences.

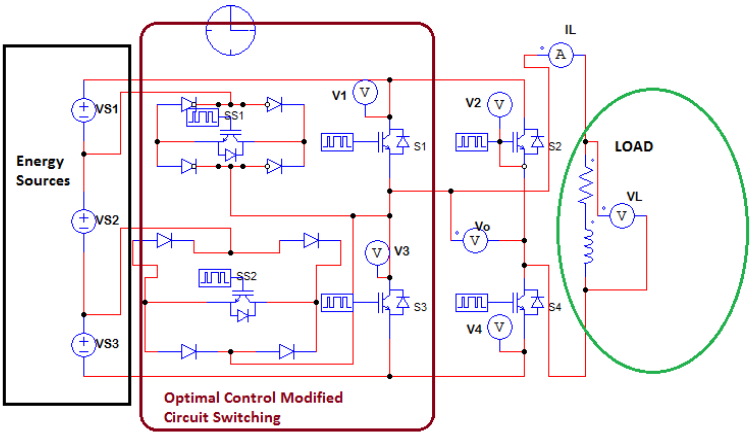


Figure 4. Simulation model of converter with optimal switching in PSIM

Table 2. Switching structure

Voltage levels (V)	Active switches	Inactive switches
V1+V2+V3	S_1 S_4	S_2 S_3 S_5 S_6
V1+V2	S_4 S_5	S_1 S_2 S_3 S_6
V1	S_4 S_6	S_1 S_2 S_3 S_5
0	S_3 S_4	S_1 S_2 S_5 S_6
-V1	S_2 S_5	S_1 S_3 S_4 S_6
-(V1+V2)	S_2 S_6	S_1 S_3 S_4 S_5
-(V1+V2+V3)	S_2 S_3	S_1 S_4 S_5 S_6

4. PROTOTYPE HARDWARE SETUP (EXPERIMENTAL ANALYSIS)

A step-down transformer is used in the hardware prototype seen in Figure 5 to reduce a 230 V supply voltage to 12 V and 24 V. A diode bridge rectifier is then used to transform this lower voltage into direct current (DC) [17], [18]. The hybrid multilevel inverter's input circuit receives the rectified DC voltage as an asymmetrical source. Table 3 lists the parts needed for the hardware configuration.

Table 3. Hardware component details

S.No	Component	Model/type	Details
1	MOSFET	IRF630FP	-
2	Step-down transformer	-	0-12 V, 5 mA; 0-24 V, 5 mA
3	Diode	IN4007	-
4	Capacitors	-	1000 µF
5	Bridge rectifier IC	DB105	-
6	Optocoupler	MCT2E	-
7	Resistors	-	1 kΩ
8	Voltage regulator IC	7812, 7824	-
9	Arduino UNO	ATmega328	Input voltage: 7-12 V 14 digital I/O Pins (6 PWM outputs) 6 analog inputs 32 k flash memory Clock speed
10	LED	-	2.0-2.5 V, 50 mA

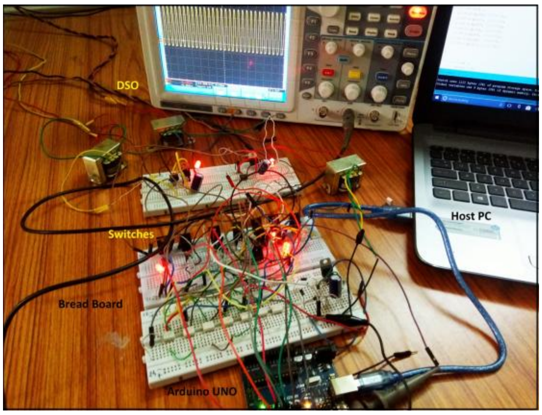


Figure 5. Simulation model of converter with optimal switching in PSIM

The driver circuit primarily serves to boost the switching voltage for the MOSFETs while maintaining isolation between the power circuit and the microcontroller circuit [19], [20]. Its output is connected across the gate and emitter terminals of the MOSFETs. An MCT2E optocoupler is employed to relay signals from the microcontroller to the driver circuit [21]-[23]. The hardware setup is integrated with an Arduino UNO, which generates PWM pulses for the MOSFETs, enabling precise and efficient control of the inverter [24]-[26].

5. VALIDATION OF SIMULATION RESULTS

The proposed modified converter for the microgrid system was simulated using PSIM, a powerful tool designed for the simulation and analysis of power electronics and motor drive systems. PSIM was employed to evaluate the performance of the converter under optimal switching control strategies, ensuring efficient operation and reliable delivery of power to the load. The primary objective of the simulation was to achieve the desired load voltage and current waveforms, which are critical for maintaining system stability and ensuring power quality. The switching control technique implemented in the converter dynamically adjusts the switching sequences of power electronic devices, optimizing the energy flow within the microgrid system. This approach minimizes losses, reduces harmonic distortion, and ensures that the load is supplied with a voltage and current waveform closely matching the required specifications. As depicted in Figure 6(a), the simulation results illustrate the precise and stable load voltage waveform achieved through the proposed converter design. Similarly, Figure 6(b) demonstrates the corresponding load current waveform, which is smooth and free from significant distortions, indicating the effectiveness of the switching control strategy. These results validate the performance of the modified converter, showcasing its ability to meet the microgrid system's operational requirements while enhancing efficiency and reliability. The simulation highlights the potential of this approach to improve the overall performance of hybrid energy systems in real-world applications.

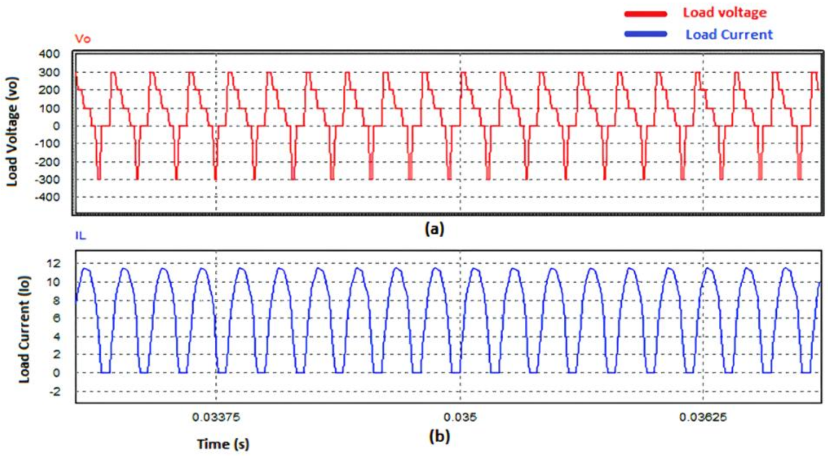


Figure 6. Simulation of (a) load voltage and (b) load current

The suggested converter for the micro grid system has a prototype hardware installed in the laboratory. In Channels 1 (CH-1) and 2 (CH-2), respectively, the output voltage and load current waveforms obtained from the DSO are shown in Figure 7. It is clear from the wave structure that the load current is pulsating DC and that the seven level voltages have been attained. As a result, the output load current and voltage are verified. According to Figures 8 and 9, the overall harmonic distortion is 3.7% of the load voltage and 1.7% of the load current of the fundamental frequency, respectively.

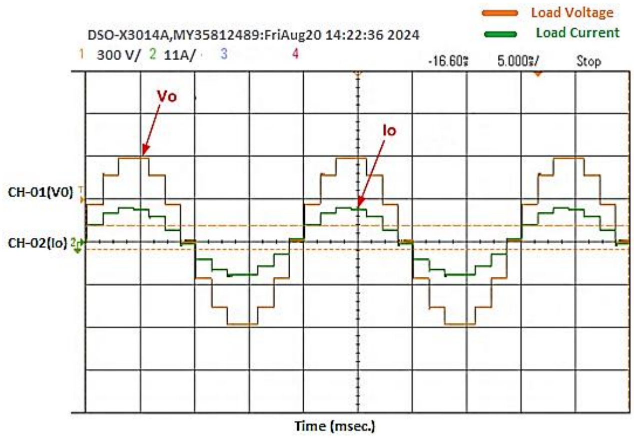


Figure 7. Load voltage and load current (experimental)

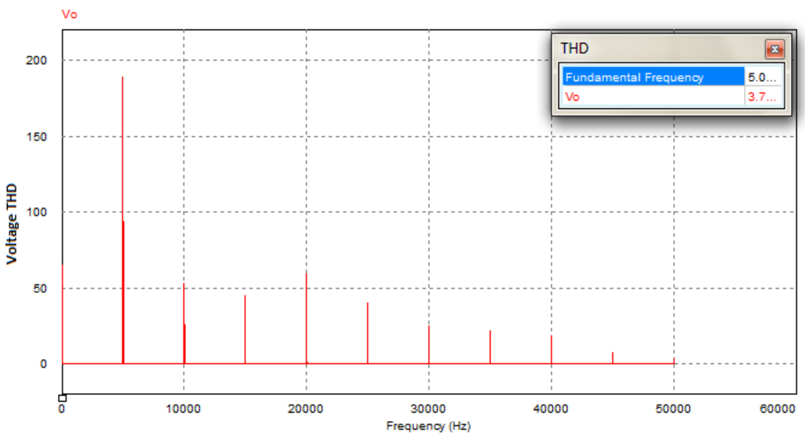


Figure 8. % THD analysis of load voltage

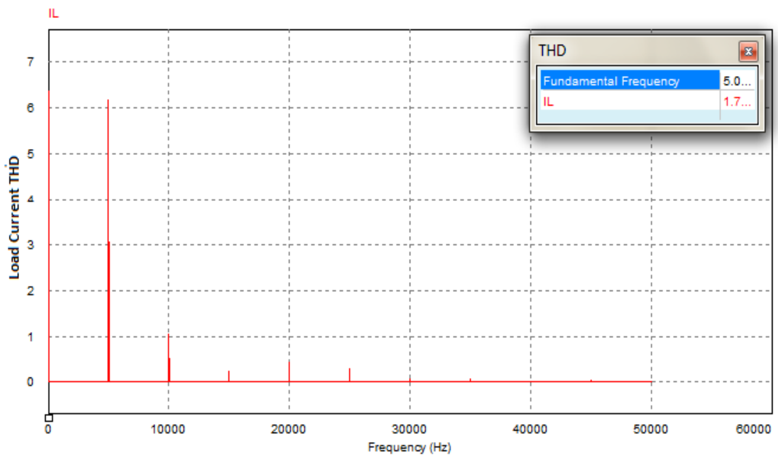


Figure 9. %THD analysis of load current

6. CONCLUSION

The study highlights the techno-economic feasibility of microgrid systems for rural electrification, specifically in Tendua. The PV/hydro microgrid system offers a sustainable and cost-effective solution, providing reliable electricity while reducing dependency on fossil fuels. The outcomes suggest that hybrid renewable energy systems could play a critical part in addressing India's rural energy challenges, particularly in areas with abundant natural resources like solar and hydro potential. Additionally, the PSIM software is used to evaluate the converter operation performance through optimal control strategy, and the output from the converter is observed as near to sinusoidal. The converter performance with the multiple energy sources for the micro grid is also validated through the hardware setup. Thus, such systems can contribute to energy sector, rural development, and environmental sustainability. This study underscores the importance of supporting renewable energy initiatives and subsidizing initial costs to enable widespread adoption in rural areas.

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BIOGRAPHIES OF AUTHORS

Pritha Gupta currently working as assistant professor in the department of Electrical Engineering, Bhilai Institute of Technology Engineering College, Durg, Chhattisgarh, India. She holds a B.E. degree with first class (Hon.) in Electrical & Electronics Engineering from Chhattisgarh Swami Vivekananda Technical University, Bhilai, India in July 2010, she obtained her M.E. degree in Power Electronics from CSVTU, Bhilai, India. in March 2013. She has authored many research papers. Her areas of research interest are power electronics, optimization techniques, power quality improvement, and control techniques. She can be contacted at email: prithagupta.25@gmail.com.

Dr. Mahesh Singh currently working as associate professor in the Department of Robotics and Automation Engineering, Symbiosis Institute of Technology (Deemed University), Pune, India. He holds B.E. degree with Honors in Electrical Engineering from Pt. Ravi Shankar Shukla University, Raipur, India in August 2004. He obtained his M.Tech. with first class (Hon.) from Chhattisgarh Swami Vivekananda Technical University, Bhilai, India in July 2009 and PhD in Electrical Engineering from Swami Vivekananda Technical University, Bhilai (C.G.) He is member of IEEE and Institute of Engineers (IE). He has authored papers in 11 International Journals and Conferences and 14 National conferences. His areas of research interest are power system stability control, optimization technique, power quality improvement, and control technique. He can be contacted at email: singhs004@gmail.com.

Dr. Shimpy Ralhan is a Professor of Electrical Engineering at the Shri Shankaracharya Technical Campus, where she has been teaching for over 23 years. Her research focuses on optimization in electric power systems, application of artificial intelligence to relay coordination, modeling, simulation & design of intelligent controllers, renewable energy sources, and grid integration. She has published extensively in peer-reviewed journals and conferences. When she is not working on research or teaching, she enjoys mentoring young scholars. She can be contacted at email: shimpy.ralhan@sstc.ac.in.

Dr. Mangal Singh is working as an Associate Professor, Electronics & Telecommunication Engineering at Symbiosis Institute of Technology, Symbiosis International (Deemed University), Pune. He has an experience of more than 22 years in the field of Teaching, Research and Administration. He obtained his graduation in Electronics and Telecommunication Engineering from National Institute of Technology (formally known as GEC), Raipur, Chhattisgarh, and M.Tech. in Communication Engineering Jadavpur University, Kolkata, West Bengal. Dr Singh obtained his Ph.D. in Communication Engineering from National Institute of Technology, Rourkela, Odisha. He has served as Associate Professor, Electronics & Communication Engineering, Institute of Technology, Nirma University, Ahmedabad and Associate Professor, Electronics & Communication Engineering, Chhatrapati Shivaji Institute of Technology, Durg, Chhattisgarh. He has published several research papers in the area signal processing for communications, particularly multi-carrier modulation (OFDM) for wireless communication systems in International refereed/peer-reviewed Journals and presented/published more than 20 papers in National/International Conferences/Proceedings. He has 3 Indian patents published and one Australian patent grant in his credit. He has guided several PG/ PhD dissertations. He is a Senior Member of IEEE and life member of the IETE and ISTE, India. He can be contacted at email: mangal.etce@gmail.com.