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Commissioning and Field Validation of a PV/Diesel Hybrid Plant in Rural Burkina Faso

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Abstract

Designing hybrid power plants is a crucial aspect of deploying energy sources in remote rural areas far from the power grid. Many studies have been conducted on this topic. However, there is a lack of information on the process of commissioning and evaluating the performance of these plants, specifically for photovoltaic-diesel hybrids. The suggested approach involves conducting three types of tests: "generator only", "multi-generator", and "hybrid". The methodology helps investigate the behaviour and performance of generators, load distribution and current quality. It was implemented in a hybrid PV/diesel plant in Burkina Faso, where it revealed technical shortcomings that hindered optimal performance. The power output of the Diesel generators deviated from the manufacturer's specifications, with diesel generators only producing 65 - 80% of their rated capacity during testing. Moreover, a malfunction in the voltage regulator of Diesel generator 2 prevented it from operating in parallel with the others. The photovoltaic arrays, however, operated efficiently, maintaining an average global efficiency of around 83%. In terms of protection, testing revealed that a reverse power relay is needed to protect each diesel generator, as it may be damaged by reversed power. It is crucial to mention that the EN 50,160 standard's electrical quality requirements were fully met, with total harmonic distortion consistently below 8%. This methodology may serve as a guide for commissioning rural hybrid power plants in sub-Saharan Africa and other regions.

Keywords

Hybrid PV/Diesel, Performance, Commissioning, Burkina Faso

1. Introduction

Africa is experiencing rapid demographic growth, which is closely linked to a steadily increasing demand for energy services [1]-[3]. Access to electricity is a key driver of economic development and a fundamental factor in improving living conditions, making it an undeniable catalyst for progress. The African energy sector has seen significant progress in meeting the electricity needs of its population. The trend is very encouraging; indeed in 2001, the New Partnership for Africa's Development (NEPAD), which is an agency of the African Union, had set development goals for the energy sector in Africa. One of the objectives was to reach, within twenty years, the rate of 35% of the population having access to reliable and affordable energy [4]. Now, almost two decades later, significant progress has been made, but there is still work to be done, particularly in sub-Saharan Africa. Indeed, the electrification rate in this part of Africa is around 53.3% on average levels and 33.9% for rural areas (The World Bank, World Development Indicators 2023). These electrification rates indicate that rural areas need specific solutions to rapidly meet the energy needs of their populations. Knowing that rural areas in sub-Saharan Africa concentrate around 57% of the total population (The World Bank, World Development Indicators 2023), this important section of the population cannot be kept aside from electrification and development efforts. From that perspective, a large number of scientific studies have recommended the use of hybrid renewable energy systems to address the electrification issue in rural communities far from the electric grid [5]-[7]. They can be defined as mechanisms that use several interconnected energy sources for the production of synchronised energy. They allow sharing the advantages of the different energy sources, while minimising the weaknesses of each one of them. Hybrid renewable energy systems are becoming increasingly common in meeting the energy needs of rural and peri-urban populations. This trend is particularly evident in sub-Saharan Africa, where the use of PV/Diesel installations is on the rise in countries such as Burkina Faso. The concern about these technologies is justified by the numerous benefits that arise from their use, among which:

- Increase in the renewable energy proportion in the global energy mix;
- Reliability and continuity of energy production, while the intermittency of the solar source is softened;
- Savings are made by avoiding National Grid extensions, which sometimes are not cost-effective;
- Effective means for the extension of energy services to rural areas.

Numerous studies have examined the sizing of hybrid power plants that combine solar photovoltaic (PV) and diesel generators, includ ing [8]-[14]. Despite this extensive body of knowledge, there is a relative lack of focus on testing and commissioning these systems to ensure optimal performance. To address this deficiency, a performance analysis of a hybrid PV/diesel plant was conducted using Matlab and Simulink in [15]. [16] used the HOMER software to analyse the performance of a hybrid PV/diesel plant in Saudi Arabia's western region. In a similar vein, [17] evaluated the performance of an off-grid solar system on Legundi Island, Indonesia, using the Homer software. [18] conducted a performance evaluation of a hybrid PV diesel system using a theoretical and experimental study. [19] Improved the performance of a PV/diesel plant using an energy storage system.

These studies revealed a lack of in-depth evaluations in this field, as most of them heavily rely on computer simulations. Moreover, many researchers who use experimental methods overlook crucial elements, such as:

- The individual and collective performance of diesel generators in a system;
- The distribution of electrical loads in hybrid PV power plants;
- The quality of the generated electrical current.

Our research presents a strategy for assessing the performance of a hybrid PV/diesel plant using actual testing. Analysing the hybrid facility's capabilities and limitations will reveal its full potential and boundaries. These figures are crucial during the initial stage, as they promote confidence, reduce hazards, and ensure reliable power. The object of this study is a PV/diesel hybrid power plant in Burkina Faso.

To address our topics, we designed three operating modes for conducting experiments: "generator only", "multi-generator", and "Hybrid". Our strategy considers the electrical loads that power plants must meet, particularly in rural areas, where inductive charges often require reactive energy consumption [20]-[22]. This reactive energy is used to magnetise electrical circuits; it is produced for the needs of transmission lines, as well as for electric engines and other appliances. The scientific literature highlights that the production of reactive energy has an effect on the cost and quality of the electricity produced [23]-[26]. Consequently, the experiments in this study used load profiles based on three different power factors (0.8, 0.9, and 1.0). These were simulated using a load bank. This paper is divided into four distinct sections, with the first one detailing the experimental setup and materials. The second part describes the methods used, as well as the various operating modes. Then, the third part presents the results of the experiments, followed by an in-depth analysis. Finally, the conclusion ends the paper.

2. Materials and Methods

2.1. Experimental Setup

Our expiremental setup is located in a village with a rural community in Kadiogo Province, Burkina Faso's central region. The Hybrid plant is made up of three diesel generators: two of 16 kW generators (DG2 and DG3) and one of 24 kW generator (DG1). The total installed apparent power is 70 kVA. The diesel generators are displayed in **Figure 1**. In terms of renewable energy, the plant consists of five photovoltaic arrays: two 7.5 kWp and three 5 kWp arrays, bringing the total installed photovoltaic power to 30 kWp, the photovoltaic arrays are presented in **Figure 2**. The load bank used in this paper is depicted in **Figure 3** and has a total power capacity of 82.5 kVA. It is composed of six identical channels, each channel consisting of:

- Four resistors (1 × 1.1 kW, 2 × 2.2 kW, 1 × 5.5 kW);
- Four inductors (1 × 0.825 kVar, 2 × 1.65 kVar, 1 × 4.125 kVar);
- Four capacitors (1 × 0.825 kVar, 2 × 1.65 kVar, 1 × 4.125 kVar).

Figure 1. Diesel generators.

Figure 2. Photovoltaic arrays.

Figure 3. Load bank.

2.2. Instrumentation

For this task, the following equipment was employed:

- An Acculab VIC-10KG scale was used to measure mass, with a maximum capacity of 10,100 grams and an accuracy of ±2 grams;
- CA8335 network analysers with PAC93 clamps were used to measure various electrical parameters, including voltage, current, harmonics, active power, reactive power, power factor, and energy consumption. The measured values have the following accuracy: ±(0.8% + 1 V) for voltage, ±(1% + 1 A) for current, ±(2.5% + 5 pt) for harmonics, ±1% for active and reactive power, ±1˚ for power factor, and ±1% for energy.

- The generators' Inteli compact controllers were used to collect the operating and shutdown times.
- Solar irradiance is measured using a solar sensor connected to an Almemo 2290 data logger.

2.3. Operation Modes and Protocols

2.3.1. Generator Only

- ***Overview***

In "generator only" mode, each diesel generator operates under predetermined load profiles, with power factors of 0.8, 0.9, and 1. These load profiles are applied using the 82.5 kVa load bank presented in **Figure 3**. Critical metrics, such as hourly fuel consumption, efficiency, and electrical output quality, are carefully tracked using the scale, the network analysers and the generators controllers. The load profiles are set up to ensure that generators operate at specific load levels: 13.75%, 27.5%, 41.25%, 55%, 68.75%, and 100% of their rated power. Equation (1) shows how the load rate is determined, considering both the active and reactive power of the electrical loads. Before the experiment began, the fuel consumption of each generator was measured during no-load tests. These tests consisted of ten 3-minutes periods of operation under no-load conditions, with at least 15 minutes between each run. For each of the three generators, this procedure was repeated.

- ***Test protocol***

In these experiments, tests are conducted with one generator at a time. Therefore, all other generators in the plant are disconnected during the tests. The test Protocol includes the following sequences:

- Disconnect the fuel supply and return lines of the generator during testing;
- Fill an external tank with fuel;
- Insert the engine's fuel supply and return lines into the external tank;
- Place the external tank on a scale;
- Note the initial weight (m_i) wish is the combine weight of the external tank, the fuel, the suction and return line;
- Start the generator under test and run it at no load for t_{v1} = 180 seconds, then measure the final weight;
- Repeat this no-load test 10 times for adequate data;
- Configure the PLC (Programmable Logic Controller) of the load bank with the appropriate testing parameters (load profile);
- Connect the generator to the load bank;
- Begin data recording on the network analysers;
- Turn on the generator and run the load profile for a defined duration (t_{charge});
- Disconnect the generator once the load profile has been fully run;
- Stop the generator's operation after a cooling time t_{v2} between 20 and 30 seconds;
- Record the final mass reading from the balance.

This process is repeated for each load level. For each one, the hourly and specific fuel consumption, as well as the efficiency, are determined.

For each one, you will need to determine the

$$\text{Load rate}(\%) = \frac{\text{Load apparent power}(\text{kVA})}{\text{Diesel generator apparent power}(\text{kVA})} \times 100 \quad (1)$$

Equation (2) is used to calculate the mass flow rate.

$$d_m(Charge) = \frac{\left((m_i - m_f) - (t_{v1} + t_{v2}) \times d_{mv}\right)}{t_{charge}} \quad (2)$$

where:

$d_m(Charge)$ = mass flow rate(g/s) for a given load rate;

d_{mv} = mass flow rate (g/s) for no load;

(m_i) = initial mass (g), which is the total weight of the external tank, fuel, suction and return lines;

(m_f) = final mass (g), which is the total weight of the external tank, remaining fuel at the end of an experiment, suction and return lines;

(t_{v1}) = time (s) of no-load operation of the diesel generator at the start of the test;

(t_{v2}) = no-load operating time (s) of the diesel generator at the end of the test.

Equation (3) is used to obtain the specific consumption.

$$C_S = \frac{\left((m_i - m_f) - \left((t_{v1} + t_{v2}) \times d_{mv}\right)\right)}{E} \quad (3)$$

where:

C_S = Specific consumption (kg/kWh);

E = Energy produce (kWh).

Equation (4) is used to calculate the global efficiency.

$$\eta_{GD} = \frac{E_{electrical}}{PCI \times C_S} \quad (4)$$

$E_{electrical}$ = Electrical energy equivalent to 1 kWh or 3600 kJ;

PCI = Lower calorific value of diesel (43.8 MJ/kg ≈ 12.17 kWh/kg);

C_S = Specific consumption (kg/kWh).

The Equation (5) to Equation (8) were used to determine the uncertainty of type B in the mass flow rate and the specific consumption of the Diesel generators. When a value is derived from measured values of Y and Z with uncertainty, the resulting value for X is also subject to uncertainty. To determine this uncertainty $u(X)$, the uncertainty $u(Y)$ and $u(Z)$ must be considered.

$$\text{If } X = Y - Z \text{ or } X = Y + Z \text{ then } u(X) = \sqrt{u(Y)^2 + u(Z)^2} \quad (5)$$

$$\text{If } X = Y \times Z \text{ or } X = Y/Z \text{ then } \frac{u(X)}{X} = \sqrt{\left(\frac{u(Y)}{Y}\right)^2 + \left(\frac{u(Z)}{Z}\right)^2} \quad (6)$$

$$\text{If } X = Y^n \text{ then } \frac{u(X)}{X} = n\frac{u(Y)}{Y} \quad (7)$$

$$\text{Finaly } X = x \pm U(X) \quad (8)$$

$U(X)$ is the uncertainty expanded to 95% confidence. With $U(X) = 2 \times u(X)$.

2.3.2. Multi-Generator Mode

- ***Overview***

This phase examines the performance of parallel diesel generators. Two or more generators are required to meet electrical demands. The experiment focuses on load distribution and current quality. To facilitate this phase, a set of load profiles with power factors of 0.8, 0.9 and 1 were established. Generator 2's voltage regulator malfunctioned, stopping it from being paralleled with other generators. Consequently, all tests were conducted with generators 1 and 3 only. This failure to parallel generator 2 highlights the crucial importance of ensuring the hybrid plant's performance during commissioning.

- ***Test protocol***

These trials employed only generators 1 and 3. The testing procedure consisted in the following phases:

- Initiate the first generator and allow it to idle for t_{v1} = 180 seconds to reach a stable state;
- Configure the PLC of the load bank to execute a load profile;
- Begin recording data on the network analysers;
- Launch the simulation of the load profile;
- Connect the first generator to the load bank;
- Turn on the second generator;
- Connect the second generator before the first generator reaches its maximum power;
- The same approach is repeated for each load profile considered.

2.3.3. Hybrid (PV/Diesel) Mode

- ***Overview***

Hybrid tests involved studying the distribution of electrical loads among different system sources, as well as evaluating the quality of the generated current. Load profiles were developed using power factors of 0.8, 0.9, and 1. The performance of the PV arrays was assessed by calculating their global efficiency with Equation (9). The actual output power of the PV arrays was determined by the network analysers.

$$\eta = \frac{PV_{peak\ installed} \times \dfrac{G}{G_{STC}}}{PV_{measured}} \tag{9}$$

$PV_{measured}$ = Measured power of the PV array (W);

$PV_{peak\ installed}$ = Peak power of the PV array (Wpeak);

G = Measured irradiance on site (W/m^2);

G_{STC} = Irradiance under standard test conditions (1000 W/m^2);

η = Global efficiency of the PV array.

- ***Test protocol***

The tests conducted on hybrid mode as part of this work involved a generator coupled with one or more photovoltaic arrays. The following procedure is used:

- Configure the controller to implement a load profile on the Load bank;
- Start data recording on the grid analysers;

- Start the generator set under test and operate at no-load for a period of at least 180 seconds;
- Start the load profile simulation;
- Connect the generator to the RLC load bank;
- Connect the photovoltaic array(s) involved in the test;
- Disconnect the photovoltaic array(s) at the end of the test;
- Disconnect the load from the generator;
- Run the generator at no-load for approximately 5 minutes; Stop the DG.

3. Results and Discussion

3.1. Generator Only

Figures 4-6 show the fuel consumption of diesel generators 1, 2, and 3, respectively, as a function of their load factor. The consumption pattern is similar to the hourly fuel flow rate depicted in the graphs, with a "k" factor applied to the consumption values.

The data from Figures 4-6 suggest that the indicated load rate experimented do not exceed 80%. During testing, we noticed that the generators stopped operating before their maximum output power specified by the constructer. Although each alternator met the expected power range, the actual output of the generators fell short of the expected values. These findings suggest that the performance of the generators does not align with expectations. Several possible reasons [27]-[31] can explain these underperformance of the generators:

Overload protection, fuel issues, incomplete combustion, cooling system faults, speed governor malfunction, voltage regulator deficiency and undersize of the engine driving the alternators. These findings will guide us in identifying specific solutions.

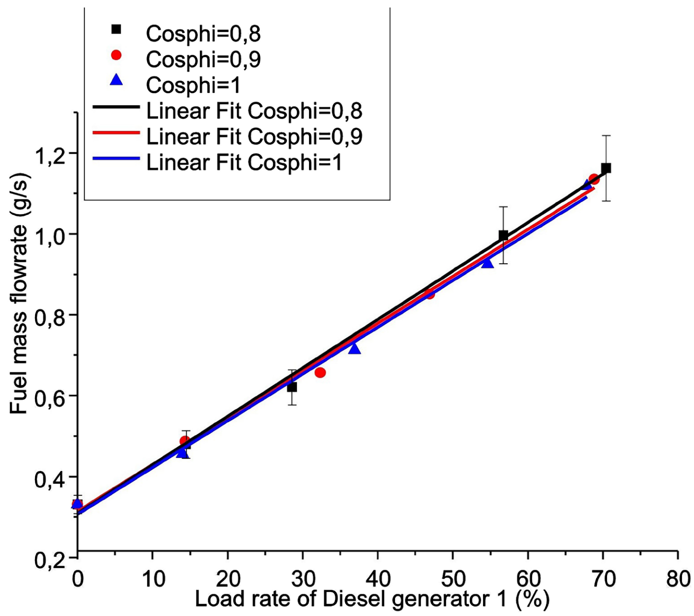

Figure 4. Fuel mass flow rate of Diesel generator 1 (g/s).

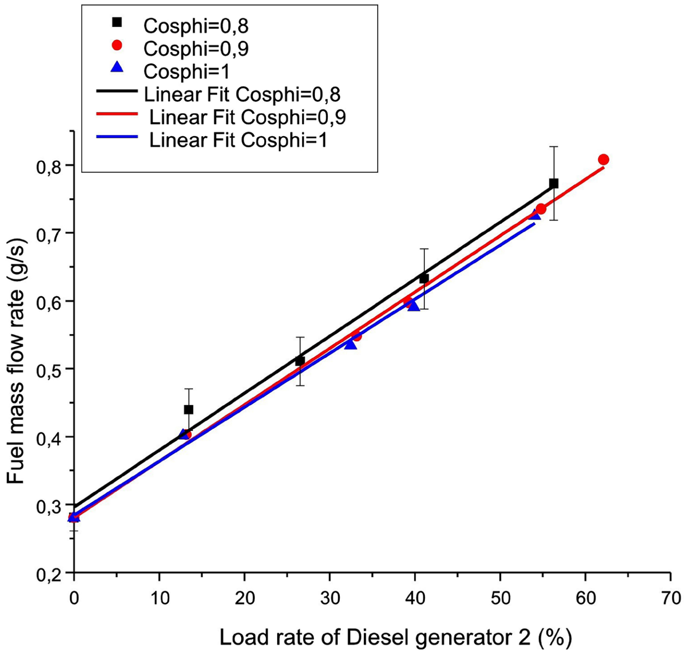

Figure 5. Fuel mass flow rate of Diesel generator 2 (g/s).

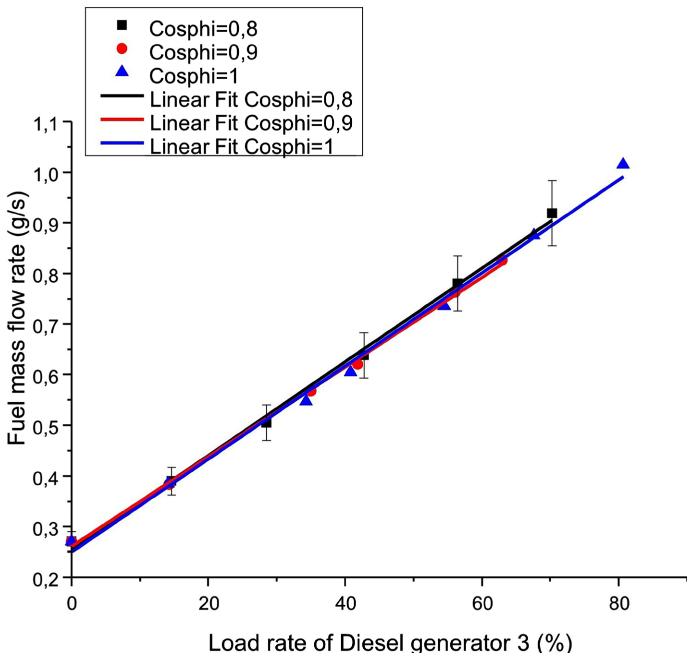

Figure 6. Fuel mass flow rate of Diesel generator 3 (g/s).

Figure 4 and **Figure 5** depict an increase in fuel consumption as the power factor decreases. However, **Figure 6** reveals a surprising finding: the maximum consumption occurs at a power factor of 0.8. This is followed by consumption rates for power factors of 1.0 and 0.9. Interestingly, all three figures exhibit a high correlation coefficient of 0.99, with relative uncertainty levels of around 7%. Although the effect is visible in the figures, due to the uncertainty level we were not able to assess the impact of the power factor on the consumption of Diesel generators in the range from 0.8 to 1. **Figures 4-6** are similar to the findings of [32], who exclusively used active power to derive his results.

Figures 7-9 illustrate the specific fuel consumption of Diesel Generators 1, 2 and 3. These values were derived using Equation (3) and are remarkably similar to the mass flow rate curves (**Figures 4-6**).

The correlation coefficients are all around 0.99 with a relative error rate of approximately 7%. The results obtained were not sufficient to evaluate the effect of the electrical equipment's power factor on generator fuel consumption, as it ranges from 0.8 to 1.0. The specific fuel consumption curves obtained are all similar to those in [33] [34].

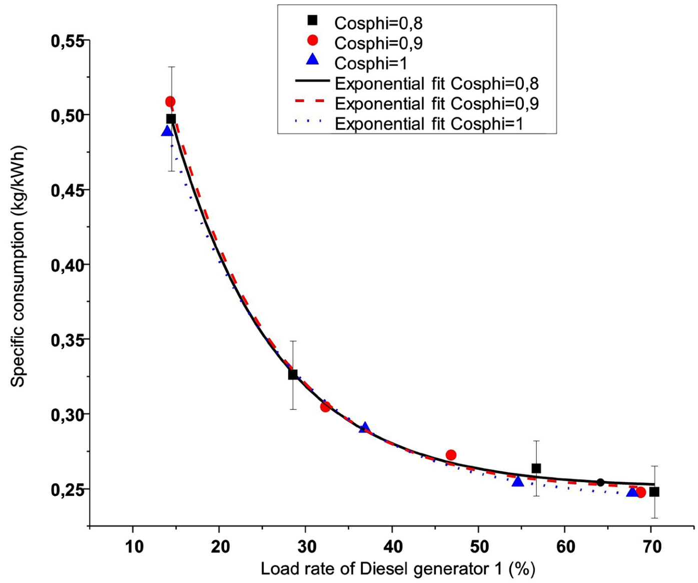

Figure 7. Specific consumption of Diesel generator N˚1.

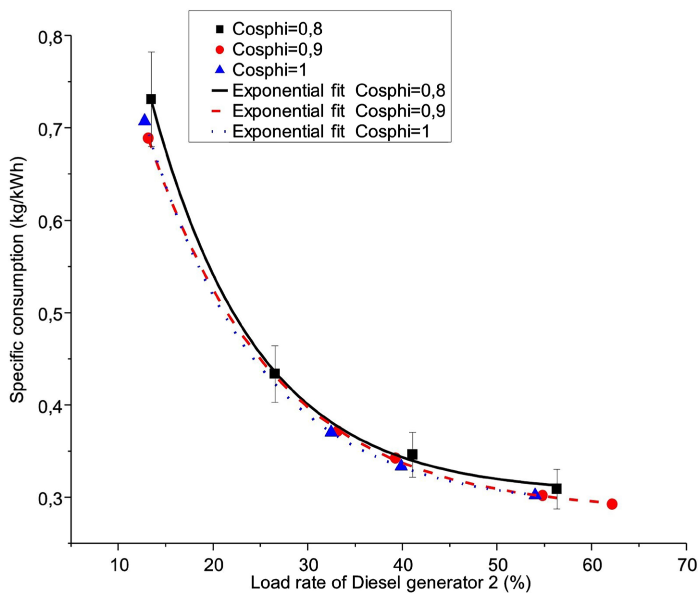

Figure 8. Specific consumption of Diesel generator N˚2.

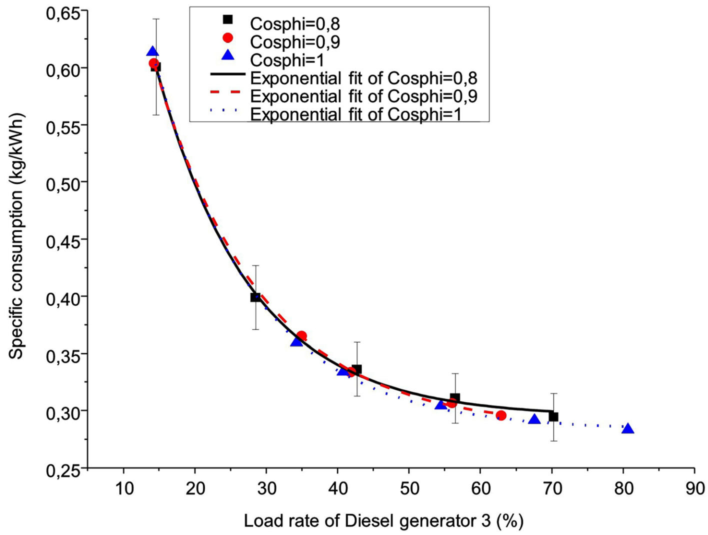

Figure 9. Specific consumption of Diesel generator N˚3.

Figure 10 shows the Diesel generators efficiencies and was obtained using Equation (4).

Figure 10 shows that generator 1 is the most efficient. Furthermore, the analysis shows that Diesel generators 2 and 3 have very similar efficiencies. This can be explained by the fact that they have the same nominal power. However, we note that during the tests, generator 3 was able to meet electrical loads up to 80% of its nominal power. Generator 2, on the other hand, could not meet loads exceeding 65% of its nominal power. The efficiency curves are consistent with the usual efficiency curve of a diesel engine, as shown in [35] [36].

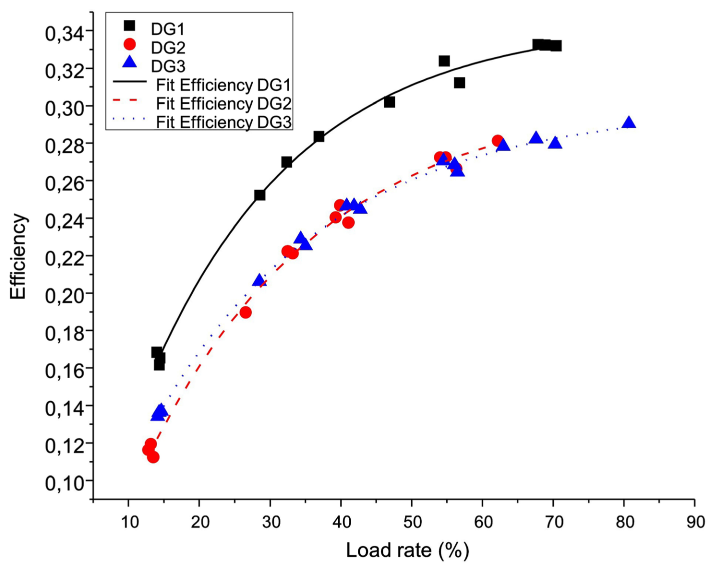

Figure 10. Efficiency of Diesel generator N˚1 to 3.

3.2. Multi-Generator Mode

This section presents the results obtained when diesel generators 1 and 3 are running in parallel. **Figures 11-13** show the distribution of active loads (a), the distribution of reactive loads (b), and the load profile for power factors of 0.8, 0.9, and 1. **Figures 14-16** focused on the quality of the generated.

Analysis of **Figures 11-13** shows that the sharing of active loads takes place in a proportionate and stable manner throughout the duration of the tests under power factors 0.8, 0.9 and 1. Indeed, the higher the generator's nominal power, the more it will contribute to satisfying the load profile. Reactive loads, for their part, are distributed in a proportionate and relatively stable manner for power factors of 0.8 and 0.9. Interestingly, when the power factor is 1 (as shown in **Figure 13**), generators 1 and 3 exhibit alternating positive and negative contributions to

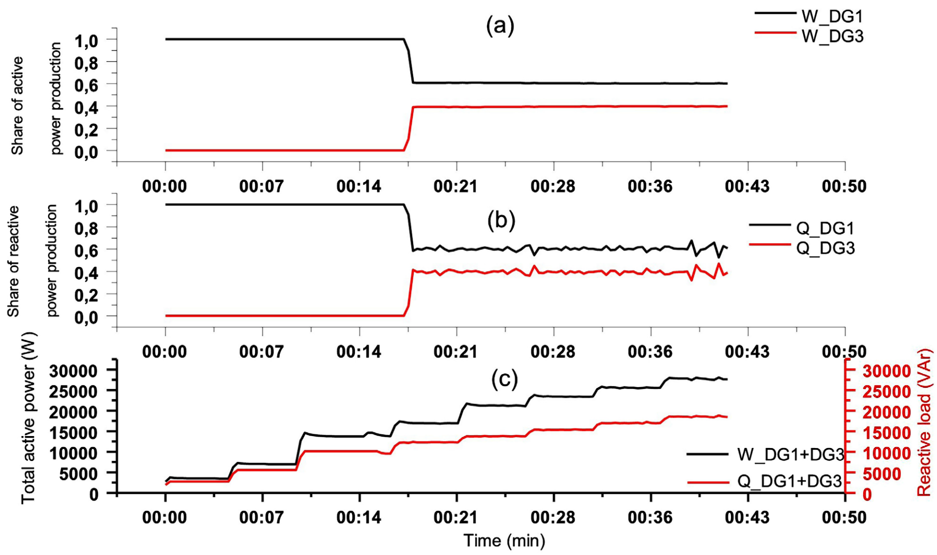

Figure 11. (a) Share of active power; (b) Share of reactive power; (c) Load profile under 0.8 power factor.

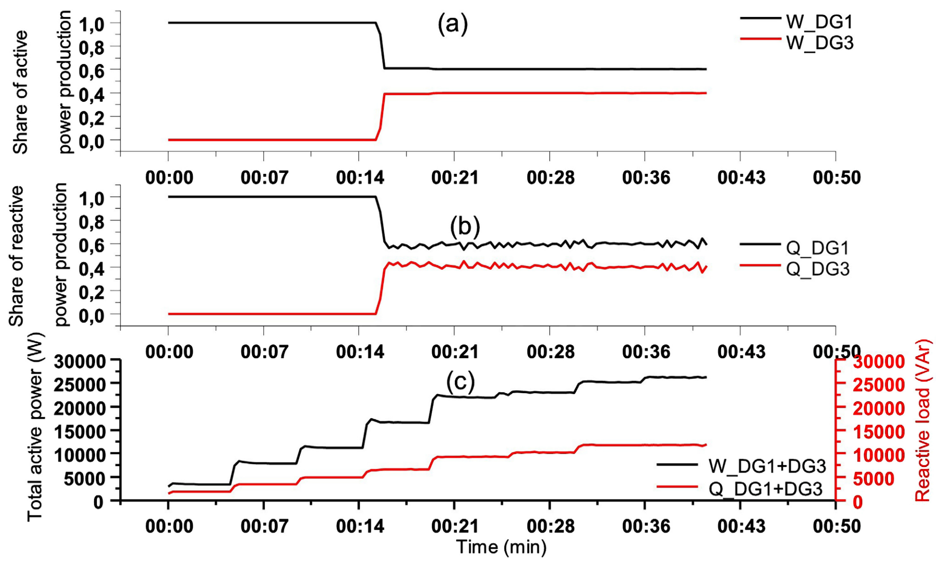

Figure 12. (a) Share of active power; (b) Share of reactive power; (c) Load profile under 0.9 power factor.

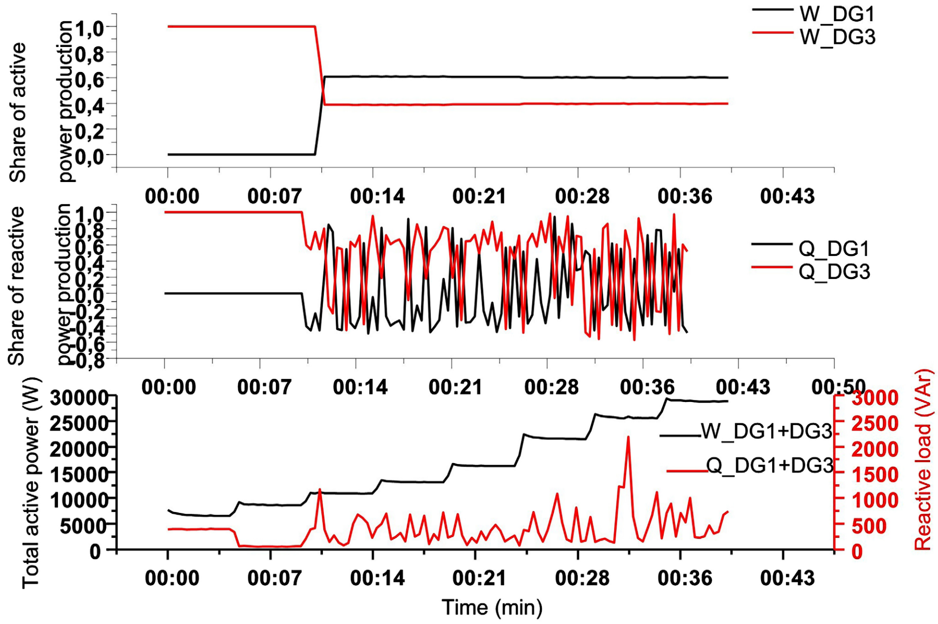

Figure 13. (a) Share of active power; (b) Share of reactive power; (c) Load profile under 1 power factor.

reactive power. This behaviour suggests that the generators alternately absorb and supply reactive power. Despite the system loads being purely resistive, significant reactive power flows are recorded. This apparent contradiction highlights the effect of excitation system dynamics and control limitations, which may lead to oscillatory or imprecise regulation when the reactive power demand is very low [37] [38]. An analysis of the quality of electricity produced in cases of parallel operation of generator sets was also carried out in this section. **Figures 14-16** present in detail the elements for assessing the quality of electricity in the above-mentioned cases. It appears that the voltage variations during experiments under power factors 0.8; 0.9 and 1 remain within the ranges recommended by the EN 50 160 standard (±10%). In addition, the harmonic distortion rate remains below 8%, as recommended by the BT EN 50 160 standard. The failure of the voltage regulator on DG2 introduces a limitation on the findings of the multi-generator performance assessment. Indeed, although the load-sharing dynamics were quite informative with DG1 and 3, DG2's non-participation may have affected the load-sharing dynamics. Therefore, the generalisation of the results obtained for parallel diesel operations is limited.

3.3. Hybrid Mode

In this section, we present the results obtained with two hybrid configurations:

- Diesel generator 1 + PV1 (photovoltaic array 1);
- Diesel generator 3 + PV 1 + PV3 (photovoltaic arrays 1 and 3).

The outcomes were found to be extremely consistent across various power factors. As a result, the data discus sed in this section comes from a power factor of 0.8. **Figure 17** and **Figure 18** show the results of the two different configuration experiments. Each figure displays the load profile satisfaction using various energy sources. The left y-axis represents the load profile, generator power and solar array power. The right y-axis shows the irradiance profile during the test. In both

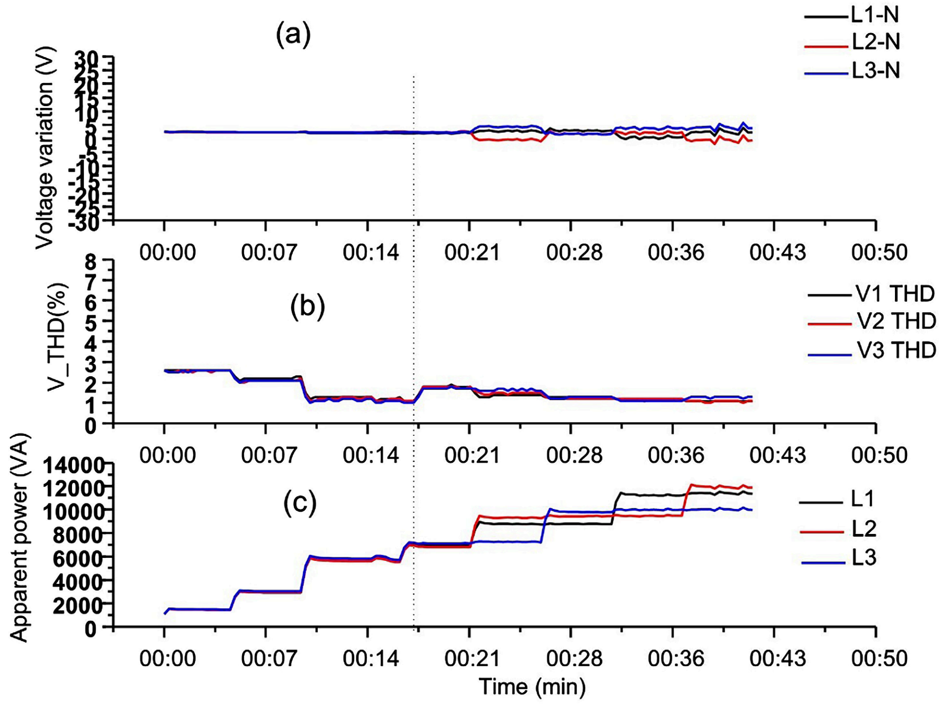

Figure 14. (a) Voltage variation ; (b) Total harmonic distorsion ; (c) Total apparent power under 0.8 power factor.

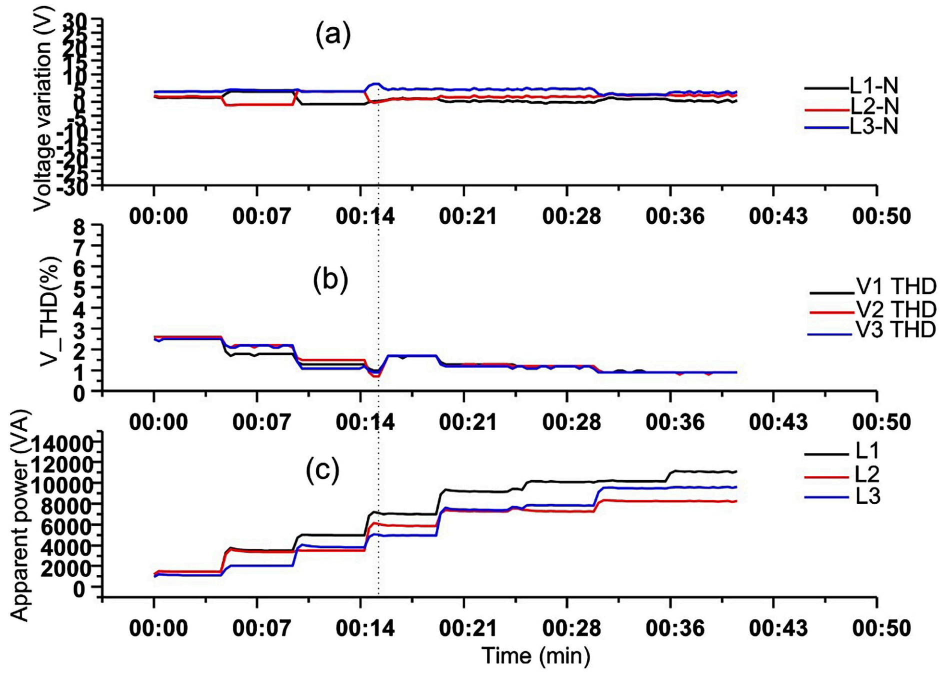

Figure 15. (a) Voltage variation ; (b) Total harmonic distorsion ; (c) Total apparent power under 0.9 power factor.

cases (**Figure 17** and **Figure 18**), the irradiance was declining while the load profile was increasing as to the contribution of the diesel generators. When calculating the global efficiency of the arrays using Equation (9), it was shown that they were always above 80%, which could be considered satisfactory.

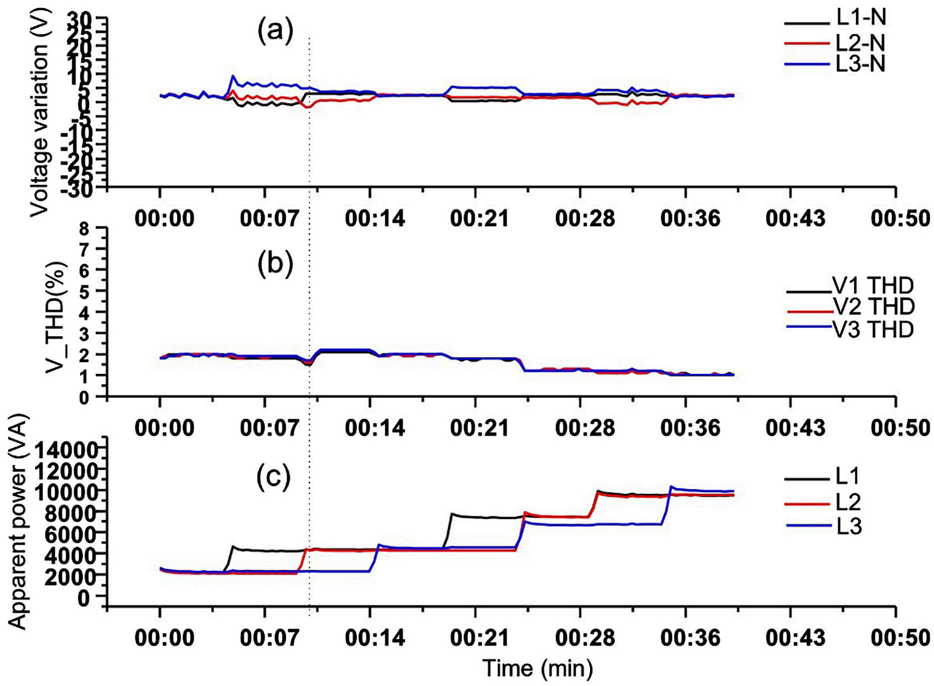

Figure 16. (a) Voltage variation ; (b) Total harmonic distorsion ; (c) Total apparent power under 1 power factor.

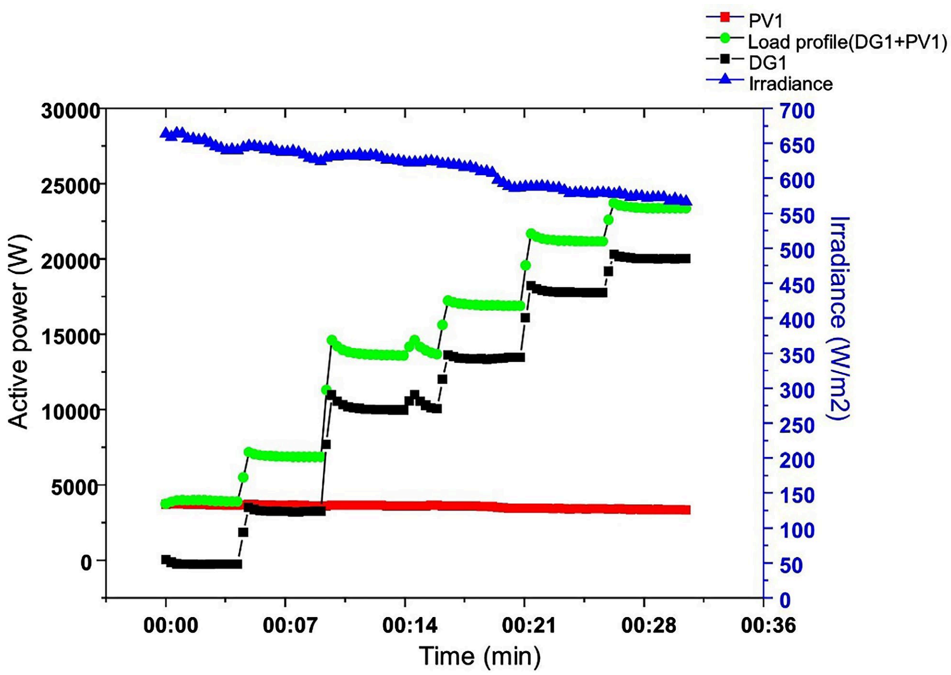

Figure 17. Meeting a load profile under 0.8 power factor in hybrid mode.

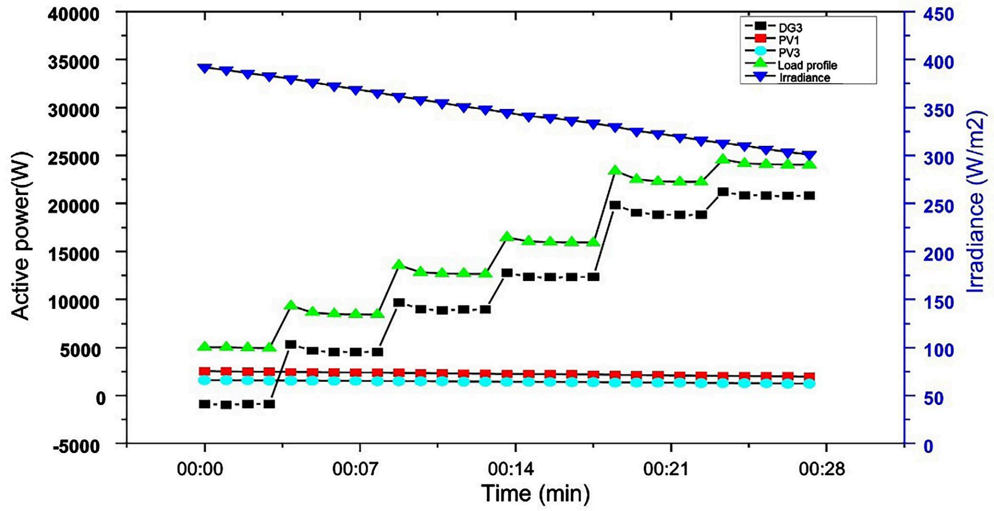

Figure 18. Meeting a load profile under 0.8 power factor in hybrid mode with (Generator3 and PV1 and PV3).

At the beginning of the trials, solar energy penetration was extremely high, leading to reverse power flow in some instances.

During the experiments, we observed that the output of the PV arrays slightly followed the irradiance shapes. However, the generators' output followed the load profile. This result can be explained by the MPPT (Maximum Power Point Tracking) function of the inverters. The inverters inject the maximum available power at each instant. This configuration gives PV arrays precedence over diesel generators, which only provide supplementary energy to match load requirements. The identical conclusions emerge from [39] [40].

Regarding the power quality parameters during the tests on hybrid modes, they all conduct to the same findings. Therefore, only **Figure 19**, which provides a comprehensive analysis of electricity quality for the hybrid configuration consisting of Diesel Generator 1 and PV1, will be discussed. This figure represents: (a) voltage fluctuations, (b) harmonic distortion, (c) the active power share, (d) the reactive power share, and (e) the total apparent power.

The voltage fluctuations remained within 10% of the recommended limit throughout the test, as outlined by the EN 50 160 standard. The harmonic level, initially at 4.5%, gradually decreased to below 1% over a period of 36 minutes. This trend can be attributed to the fact that at the beginning of the test, solar energy penetration was almost 100%, with occasional returns of power to the diesel generator. The harmonic rate gradually fell during the experiment with the increase in electrical load and the contribution of the Diesel generator, somehow it always stayed in the admissible range recommended by standard EN 50160. Although no damage occurred during the returned power cases, it is crucial to include reverse power relays in such plants to protect the generators.

Regarding reactive energy, we see that the PV array neither consumes nor produces reactive power.

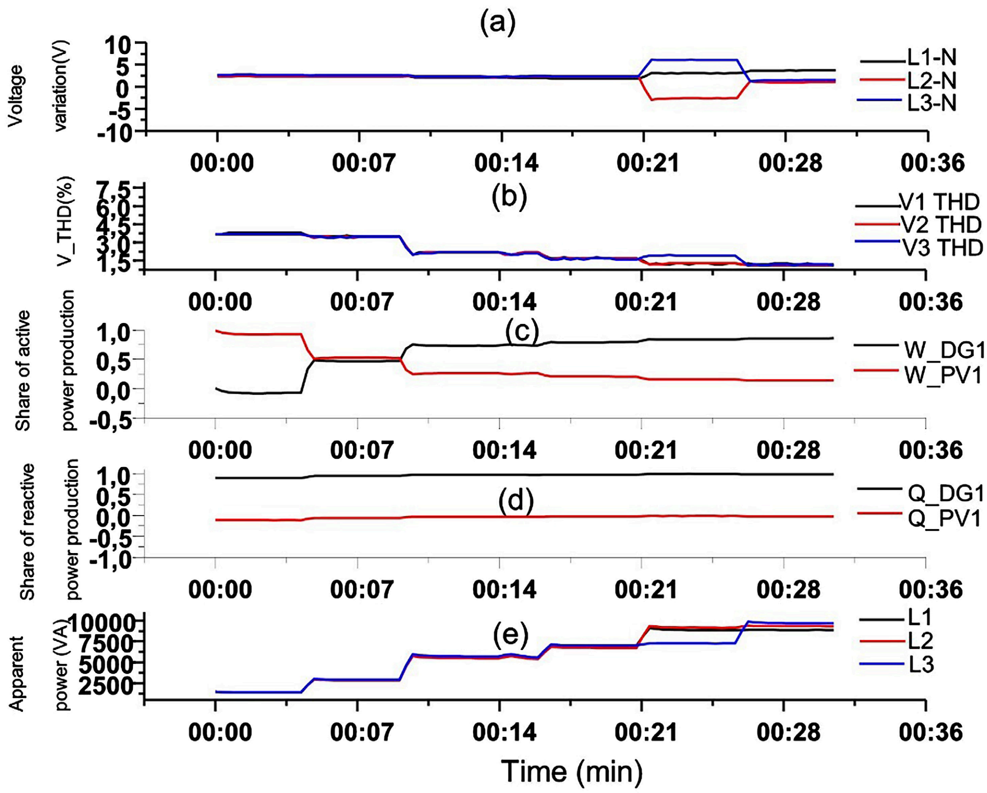

Figure 19. (a) Voltage variation; (b) Total harmonic distorsion; (c) Share of active power; (d) Share of reactive power; (e) Total apparent power under 0.8 power factor.

4. Conclusions

A methodology was proposed for the commissioning and performance evaluation of a hybrid PV/ Diesel plant on site. This methodology based on three major steps: "generator only"; "multi-generator" and "Hybrid", was applied to a hybrid power plant located in Burkina Faso. The methodology consisted of several experiments .

- Generator-only experiments made it possible, on the one hand, to note the limitations of the generators in relation to their stated nominal power outputs. On the other hand, the experiments conducted led to the conclusion that the power factor does not significantly affect the consumption of the various electrical generators, if they operate within a power factor range between [0.8 - 1].
- Multi-generator experiments allowed us to observe proportionality in the distribution of electrical loads (active and reactive). Furthermore, they also revealed that a power factor as close as possible to 1 could cause excitation loss situations. This issue must be taken into account when considering reactive energy compensation.
- Hybrid experiments allowed us to observe operations with high solar energy penetration rates. However, no power quality parameter exceeded the ranges recommended by the standards. In all the tests conducted, voltage variations remained within the ranges permitted by the EN 50160 standard (±10%). Furthermore, harmonic distortion rates were always below 8%, as recommended

by the EN 50160 standard. In addition, it was proved by the experiments the serious need of reverse power relay to protect the diesel generators as reverse power could happen during high solar PV penetration.

This work has allowed us to experimentally study the real performance of the different generators in the power plant. This knowledge will make it easier for developers of such a system to provide sustainable solutions to meet people's energy needs. The methodology proposed can, therefore, be applied to similar projects in sub-Saharan Africa or other regions.

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Conflicts of Interest

The authors declare no conflict of interest.

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