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Study and Design of a DC/AC Energy Converter for PV System Connected to the Grid Using Harmonic Selected Eliminated (HSE) Approach

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Abstract

Nowadays, distributing network-connected photovoltaic (PV) systems are expanded by merging a PV system and a Direct Current (DC)/Alternating Current (AC) energy converter. DC/AC conversion of PV energy is in great demand for AC applications. The supply of electrical machines and transfer energy to the distribution network is a typical case. In this work, we study and design a DC/AC energy converter using harmonic selective eliminated (HSE) method. To this end, we have combined two power stages connected in derivation. Each power stage is constituted of transistors and transformers. The connection by switching of the two rectangular waves, delivered by each of the stages, makes it possible to create a quasi-sinusoidal output voltage of the inverter. Mathematical equations based on the current-voltage characteristics of the inverter have been developed. The simulation model was validated using experimental data from a 25.2 kWp grid-coupled (PV) system, connected to Gridfit type inverters. The data were exported and implemented in programming software. A good agreement was observed and this shows all the robustness and the technical performances of the energy converter device. It emerges from this analysis that the inverter output voltage and the phase angle thus simulated are very important to control in order to orientate the transfer of the power flow from the continuous cell to cell to the alternating part. Simulated and field-testing results also show that increases in the value of the modulation factor (m) for low power output are highly significant. This study is an important tool for DC/AC inverter designers during initial planning stages. A short presentation of the design model of the inverter has been proposed in this article.

Keywords

Inverter, Modulation Index, Transistors, Power Stage, Harmonic Selective Eliminated, Photovoltaic (PV) System

1. Introduction

At the sight of the current environmental, political and economic context, the integration of renewable energies in energy production is becoming essential. Due to these multiple advantages, PV energy is one of the most promising solutions in the perspective of sustainable development and environmental protection. In recent years, the development of grid-connected PV systems has increased: growth which is reflected in technological innovations and lower costs for PV modules, but also in significant research and development efforts in the field of power electronics [1] [2]. However, the integration of PV systems in the production of electricity remains moderate as long as the injection and coupling devices are not well studied and structured [3]. The problem of reliable and satisfactory operation, from an energy point of view, of these systems, is summed up by a suitable choice of their power chains in terms of efficiency and economic factors.

The investigation on adequate power inverters and PV electronic devices is becoming necessary due to main reasons [4]. Grid-connected PV system may use a single or a double stage manner. An energy converter device designed for these systems must be adequate taking into account the various physical constraints imposed and above all the couplings present within the system to be controlled. To improve the efficiency of these energy productions, we propose a performance study of the injection devices of the energy produced by the PV systems connected to distributing network in order to improve their performance. The principal purpose of the DC /AC inverter is to provide the unity power factor. In accordance with these reasons, it is very important to check the inverter to provide the current in phase with grid voltage. Present PV-connected system configurations mainly use a single-high-capacity inverter. In these configurations, the overall system weakness increases and power yield after conversion by the inverter decreases when PV output is at less than 50% [5]. In this work, we propose an improved configuration for efficiency using the HSE approach. We model Deux switching combinations using derivation stages at equal currents to constitute an energy converter device. A study and design of this inverter have been proposed, describing its operating principle, its characteristics as well as its technical performance. The validity of the model and the performance of the control are evaluated by simulation in software simulator using experimental data from a PV generator of 25,200 Wp power, comprising 126 modules organized into 9 subfields of 14 modules, placed in derivation to the input of 9 Gridfit type 2500 W inverters.

2. Problem Description and Methodology

2.1. Principle of Operation of the Inverter

The inverter is equipped with a conversion tool (power transistors) intended to transform the direct voltage (DC) into an alternating output voltage (AC) of quasi-sinusoidal form. The main function of this inverter is to create an alternating voltage from a direct voltage. The proposed inverter takes advantage of the interconnection of two power stages. Each stage delivers a rectangular signal. These two signals are then combined to provide a quasi-sine wave output. An inductance-capacitance (LC) filter is placed at the output in order to be able to transform the output voltage into a sinusoidal voltage with low distortion rates. A change in the duty cycle of the rectangular waves regulates the output voltage.

2.2. Technical Concept of the Inverter

The basic concept of the inverter is relatively simple and does not depend on the technology used. To this end, the output voltage may, at some time, have the opposite polarity to that of the network voltage. In order to overcome this fact, the main part of the inverter consists of a semi-conductor bridge making it possible to connect each of the two input poles to each of the two output poles by means of electronic switches (transistors) [6]. However, care must be taken that no more than two switches located diagonally to each other are closed simultaneously.

Figure 1 shows the block diagram of the inverter.

This bridge, which switches according to the frequency of the network frequency, would already make it possible to supply the loads with alternating current, but it is a rectangular current whose intensity cannot be influenced. In order to be able to regulate the current and thus provide a sinusoidal current, an inductor with an iron core acting as a current accumulator is mounted at the output. Figure 2 is considered to model the inductor, in which L is the coil inductance, R_{pa} is the total parasitic AC resistor given by equation:

$$R_{pa} = R_{\theta} + R_{C} \tag{1}$$

where R_{θ} is the winding resistor and R_{C} the core resistor.

The impedance of the equivalent circuit shown in Figure 2 can be calculated by the following relation [7]:

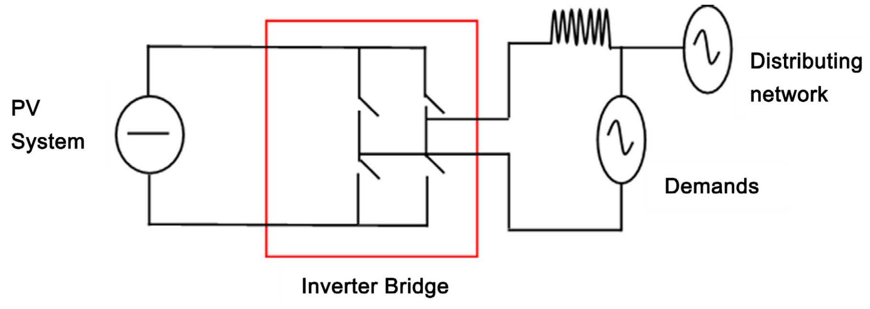

Figure 1. Block diagram of the inverter.

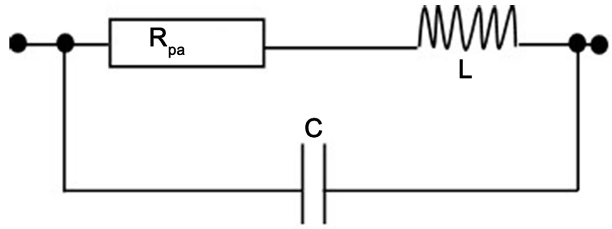

Figure 2. Equivalent circuit of the inductor.

$$Z_S = \frac{R_{pa} + j\omega L\left(1-\omega^2 LC - \frac{CR_{pa}^2}{L}\right)}{\left(1-\omega^2 LC\right)^2 + \omega^2 C^2 R_{pa}} = R_S + jX_S \tag{2}$$

where R_S is the real part, X_S the imaginary part of Z_S

The self-resonant frequency occurs when $X_S = 0$ and is defined by:

$$X_S = \frac{\omega_r}{2\pi} \tag{3}$$

The inductor parasitic capacitance is given by Equation (4), as $\frac{CR_{pa}^2}{L} \prec\prec 1$

$$C = \frac{1}{L\omega_r^2} = \frac{1}{L\left(2\pi f_r\right)^2} \tag{4}$$

The inductor quality factor at a given frequency is:

$$Q_S = \frac{X_S}{\omega} \tag{5}$$

The quality factor can be defined by using the energy stored in the magnetic field

$$Q_0 = 2\pi f \frac{E_T}{P_T} = \frac{L\omega}{R_{pa}} \tag{6}$$

where E_T is the maximum energy stored in the inductor and P_T the power loss in the total parasitic resistor.

A condenser (Cd) also acting as an energy accumulator is mounted at the input of the bridge. It ensures a continuous and homogeneous flow of the current of the generator towards the network in pulsed current with power at the frequency of the network. The basic diagram is depicted in **Figure 3**.

3. Output Wave Filtering Method

3.1. Waveform at the Output of the Inverter

A sine wave can be approached by a wave formed by steps. In this perspective, we use several voltage inverters which provide rectangular waves [7]. These voltages are then applied to the condenser input. The combination of the secondary voltages V_1 and V_2 provides a "quasi-sinusoidal" wave V. Like that can be illustrated in **Figure 4**.

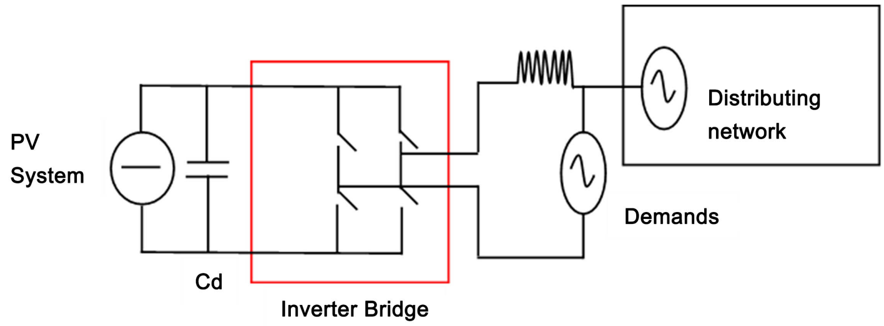

Figure 3. Basic diagram of the inverter.

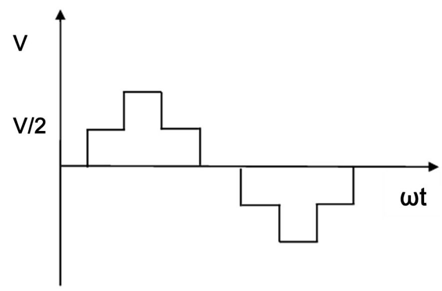

Figure 4. Representative diagram of the output wave of the proposed inverter unfiltered.

V_1 is the voltage delivered by the first inverter and V_2 that delivered by the second. The development by the Fourier series makes it possible to calculate the amplitude of the different harmonics present in the quasi-sinusoidal signal [8]. The equations allowing the calculation of these different amplitudes will be developed in the fifth section.

3.2. Inverter Output Wave Filtering

In order to have, at the output, a sinusoidal signal similar to that of the distributing network, we place at the output a filter LC which makes it possible to ensure adequate filtering of the quasi-sinusoidal wave, presented in **Figure 5**.

4. Output Wave Filtering Method

The inverter, with the associated functions to obtain the optimal interface between the PV generator and the grid, represents the pivot of the PV-Grid chain for the optimal functioning of the system [9]. After a summary of the different technologies available to ensure energy exchanges (continuous source-alternative source), some analysis has enabled us to develop an approach diagram for the proposed inverter. In order to allow acceptable operation of the inverter, tools with Well-defined functions and characteristics were studied in the design.

In this approach, the final inverter has:

- A condenser: the condenser absorbs the voltage peaks that can reach the DC input of the inverter (Input filter function).

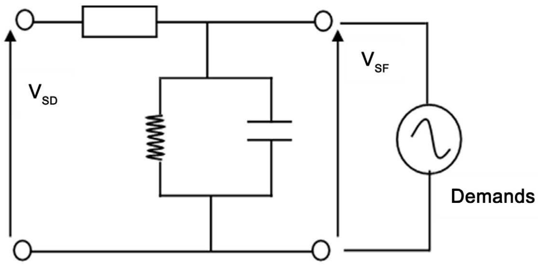

Figure 5. Representative diagram of the output filter.

- A control stage: it supplies the control signals necessary for the power stage. Control signals are formed by the combination of oscillation, regulation and protection signals.
- A power stage: the power stage is made up of electronic power switches (Transistors) which are used in switching. The conduction time of these transistors determines the period of the voltage delivered by each of the two inverters [10]. The power stage of each inverter is connected to a transformer which delivers a rectangular wave at its output. The two transformers are connected in order to obtain a quasi-sinusoidal voltage at the output.
- An output LC filter: the filter smooths the quasi-sine voltage to provide a sine wave.

In addition to these various functions associated with it, the Uninterruptible Power Supply (UPS) includes protection functions [11]:

- Against under-voltage (overvoltage) operating faults.
- Overheating (rise in temperature).
- Short circuit and overload.

The amplitude of the output voltage is regulated by acting on the conduction period of the power transistors [10]. In short, the block diagram of the proposed inverter is shown in **Figure 6**.

4.1. Principle of the Pulse Width Modulation (PWM)

The inverter has a switch which transforms the direct voltage (DC) delivered by the PV generator into alternating voltage (AC). The switch provides several positive and negative slots as shown in **Figure 7**. The fundamental magnitude of the output voltage of the inverter is controlled by exercising control within the inverter itself that is no external control circuitry is required. In this configuration the inverter is fed by a fixed input voltage and a controlled AC voltage is obtained by adjusting the on and the off periods of the inverter components. A PWM signal consists of two main components that define its behavior: a duty cycle and a frequency. The duty cycle describes the amount of time the signal is in a high (on) state as a percentage of the total time of it takes to complete one cycle.

The frequency determines how fast the PWM completes a cycle (*i.e.*, 1000 Hz would be 1000 cycles per second), and therefore how fast it switches between high and low states.

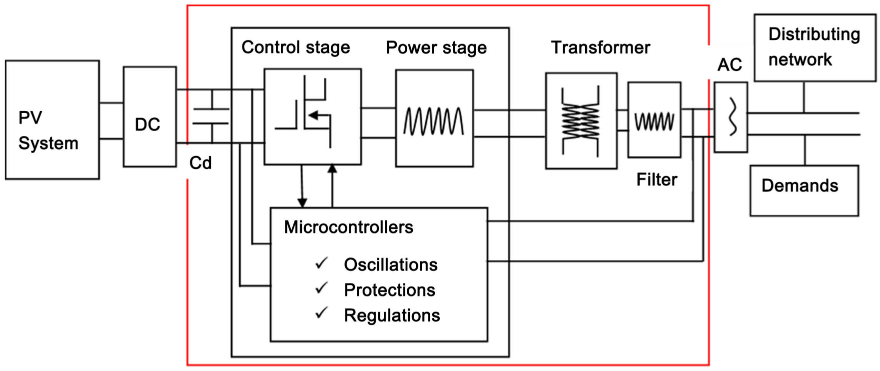

Figure 6. Block diagram of the proposed inverter.

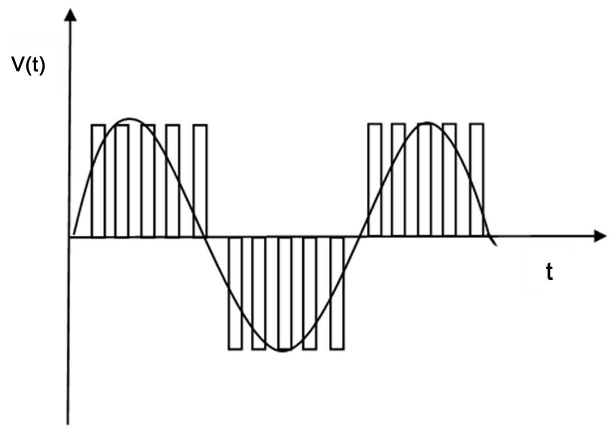

Figure 7. Pulse Width Modulation (PWM).

4.2. Brief Description of the Power Stage of the Inverter

The functional inverter is the combination of two stages connected in derivation. Each stage consists of two electronic switches and a transformer. Denote by Q_1, Q_2 the switches and T_1 the transformer of the first inverter; Q_3, Q_4 the switches and T_2 the transformer of the second. The output voltage V_1 of the first inverter is obtained by controlling the transistors Q_1 and Q_2. While the output voltage V_2 of the second inverter is supplied by the control of the transistors Q_3 and Q_4. The electrical diagram of the inverter power stage is shown in Figure 8.

The voltage V_1 is obtained at the final output of the inverter when the switch Q_5 is closed and Q_6 is opened. And conversely, voltage V_2 is supplied to the output when Q_5 is opened and Q_6 is closed. These combinations make it possible to create an almost sinusoidal voltage from two rectangular waves.

4.3. Conduction Sequence

Two pairs of switches are actuated so that their control is complementary [12]. The closing and opening of the various Q_i switches ($i = 0; 1; 2; 3; 4; 5$) allowed us to obtain the conduction sequence given in Figure 9 below.

- At t_0, the switches Q_i ($i = 1; 2; 3; 4$) are opened and the switches Q_5 and Q_6 are closed. We observe at the final output a zero signal (no voltage).

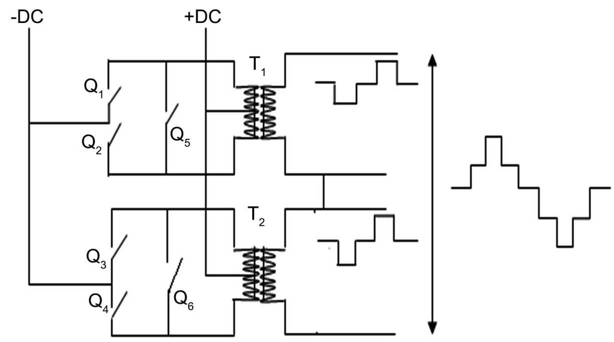

Figure 8. Electrical diagram of the power stage.

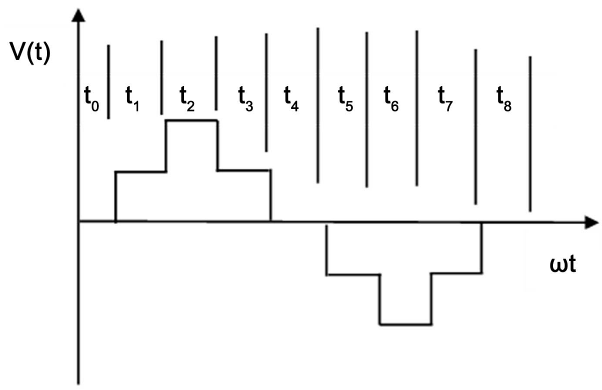

Figure 9. Diagram of the conduction sequence of power transistors.

- At t_1, the switches Q_1 and Q_6 are closed while maintaining the other switches opened.
- At t_2, switches Q_1 and Q_2 are closed, the other switches are blocked.
- At t_3, switches Q_1 and Q_6 are actuated while maintaining the others are opened.
- At t_4, the output switches Q_5 and Q_6 of the two inverters are closed, Q_1, Q_2, Q_3, Q_4 are opened.
- At t_5, closing the switches Q_2 and Q_6 provide us with the output wave thus presented.
- At t_6 and t_7, the closing of the switches (Q_2, Q_4), (Q_2, Q_6), respectively provides us with the different signals represented in these periods.
- And finally, at t_8, the switches Q_5 and Q_6 are again closed and the other switches blocked.

The closing or opening of the various transistors can be controlled by the operator or not. Switching (change of state of a switch) can be spontaneous or controlled [10]. In this electronic circuit, the switching used is controlled switching: the control is effected by sending a pulse to a terminal of the switch.

5. Method of Harmonics Selected Eliminated (HSE)

The purpose of Pulse Width Modulation (PWM) control is to decrease the harmonics present in the currents generated by the inverter [13]. In order to reduce the rate of harmonics of the output voltage and "current" of the inverter, we have used the PWM technique called "Harmonic Selective Eliminated". This HSE technique assembles a maximum (optimal) inverter waveform. Due to the double symmetry with respect to the quarter and half-wave modular period, the "direct-current" component and the even harmonics are zero (**Figure 6**) [14]. Therefore, by applying the transform from the Fourier series, we can calculate the output voltage of a PWM inverter, whose Fourier series for the output in effective value is given by the following generalized form [8]-[14]:

$$v_n(\Omega t) = \sum_{n=1}^{\infty} a_n \sin(\omega t) \quad (7)$$

where $a_n = \frac{4 \cdot V_o}{n \cdot \pi} \sum_{k=1}^{N} (-1)^{k+1} \cos(n \cdot \alpha_k)$

N: the number of switching angles per a quarter period;

n: the order of harmonic;

α_k: switching angle of rank k, which must fulfill the following condition

$$\alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 < \cdots < \alpha_N < \pi/2;$$

V_o: the input voltage of the inverter which represents the output voltage of the photovoltaic generator.

Thus, for a better quality of the power, the lowest harmonics must be eliminated. The amplitude of the harmonic of order n is zero ($a_n = 0$) for $n = \{1; 3; 5; 7; 9; \ldots\}$. The quotient between the maximum voltage of the fundamental of the inverter output and its input voltage defines the modulation factor [13].

This factor (m) is determined by the relation:

$$m = \frac{\sqrt{2} \cdot V_{SD}}{V_{ED}} \quad (8)$$

where V_{SD} is the output voltage of the inverter and V_{ED} is its input voltage. **Figure 10** shows the waveform of the output voltage of a PWM controlled inverter.

5.1. Theoretical Design of the Equivalent Circuit Model of the Alternative Part

The equivalent electrical diagram of the alternating mesh (AC) of the inverter and the Fresnel diagram of the electric circuit can be represented by **Figure 11** and **Figure 12**.

In **Figure 11**, L represents the inductance of the filter and R a parasitic resistance.

Assuming that the system is in the permanent sinusoidal state and indicating the electric quantities by their effective's values, the equations of the parameters are given as following [13]

$$V_{SD} = I_g \cdot Z_L + V_g \quad (9)$$

$$P_{SD} = V_{SD} \cdot I_g \cos(\omega t + \delta) \quad (10)$$

$$Q_{SD} = V_{SD} \cdot I_g \sin(\omega t + \delta) \quad (11)$$

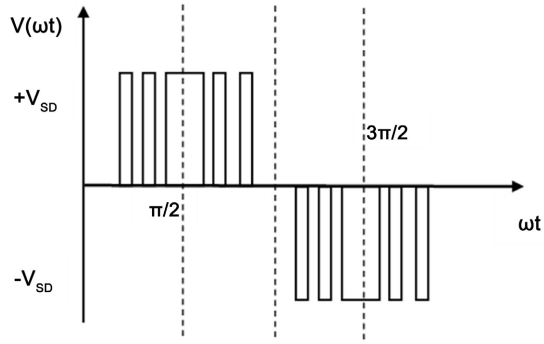

Figure 10. Diagram of the conduction sequence of power transistors.

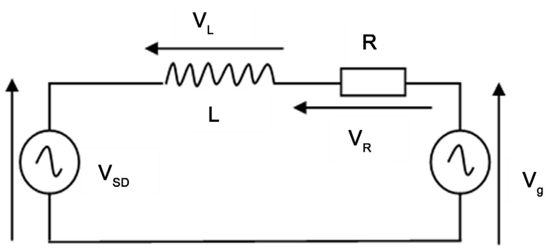

Figure 11. Diagram of the conduction sequence of power transistors.

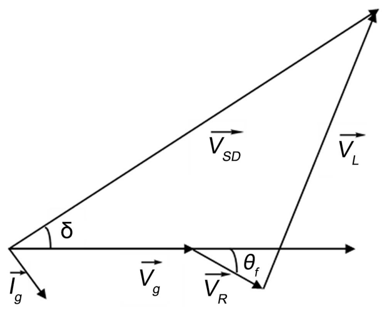

Figure 12. Fresnel diagram of the electrical circuit.

$$I_g = \sqrt{\frac{V_g^2 + V_{SD}^2 - 2 \cdot V_g \cdot V_{SD} \cos(\delta)}{R^2 + (L\omega)^2}} \tag{12}$$

where δ is the phase angle between the output voltage of the inverter relative to the voltage of the distribution grid.

P_{SD}: is the active power;

Q_{SD}: is the reactive power;

Z_L: is the inductive impedance.

The phase angle can be calculated using Equation (13) by neglecting the parasitic resistance (R) and for a unit power factor:

$$\cos(\delta) = \frac{V_g}{\frac{mV_{ED}}{\sqrt{2}}} \tag{13}$$

The efficiency or matching factor of the load can be defined as the quotient of the output power of the inverter (P_{SD}) to the power of the optimum operating point of the PV generator (P_{PPM}). The formula for the efficiency (r) of the inverter is given by [14]:

$$r = \frac{P_{SD}}{P_{PPM}} \tag{14}$$

The efficiency (r) is used to evaluate the performance of the system for different values of the switching angles of the inverter under different climatic conditions [13].

5.2. Experimental Setup

The experimental data used in this paper is based on a 25.2 kWp grid-connected PV power station in center-west Burkina. The station consists of 126 PV modules and every PV module contains 54 PV cells. The station is subdivided into 9 sub-stations of 14 PV modules. Every sub-station consists of 2 groups of 7 PV modules in series and placed in parallel to the input of 2.5 kW Gridfit type inverter [15].

The derivation setting of the 9 inverter inputs makes it possible to obtain the different characteristics of the field [13] [14]. These characteristics are summarized in **Table 1**: Peak power (P_C), maximum (U_M) and open-circuit (U_{CO}) voltages, maximum (I_M) and short-circuit current (I_{CC}).

5.3. Characteristics of the PV Array

In our study, we used data provided by Gridfit type inverters as shown in **Table 2**. The measurements provided were carried out in the center of NAYALGUE in KOUDOUGOU. These measurements were taken within 4 days of operation of the PV system [15]. For parameter calculations m and $\cos\delta$, we use Equations (8) and (13) with $V_g = 230$ V where V_g is the network voltage.

The experiments data were analyzed using a developed software simulator. The parameters to be used for the various PV productions during the four days are given below:

- The modulation index or factor (m).
- The switching angles considered correspond to the elimination of harmonics of order 3, 5, 7, 9.
- The output voltage of the inverter and its phase angle.

Simulation experiments were executed on the Gridfit type inverter model and the results are given in section 7.

Table 1. Characteristics of the PV array.

	P_C (W)	U_M (V)	U_{CO} (V)	I_M (A)	I_{CC} (A)
PV Modules	200	27.1	33.4	7.4	7.9
Sub-station	2800	189.7	233.8	14.8	15.8
PV generator	25,200	189.7	233.8	133.2	142.2

Table 2. The main parameters of gridfit type inverter.

Electrical specification	Gridfit type inverter
Nominal power AC (W)	2500
Nominal power DC (W)	2750
PV voltage to (V)	350
PV voltage from (V)	125
Euro-eta efficiency (%)	92
Max. PV power (Wp)	3300
Max. power AC (W)	2500
Max. DC voltage (V)	400
Max. current DC (A)	18
Max. efficiency (%)	94

6. Results and Discussion

Simulation is a proven tool to improve learning and also a positive environment that encourages experimentation and accepts mistakes, a very important thing in the context of learning. In order to verify the internal consistency of the various established equations or mathematical models, we propose to analyze the efficiencies of the proposed inverter by simulation. The main objective of this study is to define the performance criteria of the inverter. We also define the parameters which affect these criteria and evaluate the results obtained in order to verify the correct functioning of all the simulation models and the consistency of the results. This simulation allows us to optimize the output power of the inverter and reduce losses.

For a given PV generator and defined climatic conditions, the power P_{PPM} is fixed.

So, one of the key parameters that we have considered is the output power P_{out} of the inverter. This parameter helps to understand the behavior of the system.

In order to validate the various equations established previously, we focused our analysis on the following parameters:

- The voltage of the PV generator;
- The current of the PV generator;
- The output voltage of the inverter;
- The phase angle of the inverter with respect to the voltage of the distributing network;
- The modulation factor or index amplitude.

Figure 13 shows the variation and the range of oscillation of the amplitude modulation factor (m) for different values of PV production. The factor m which is a function of the input and output voltages of the inverter oscillates between 1.90 and 2.5.

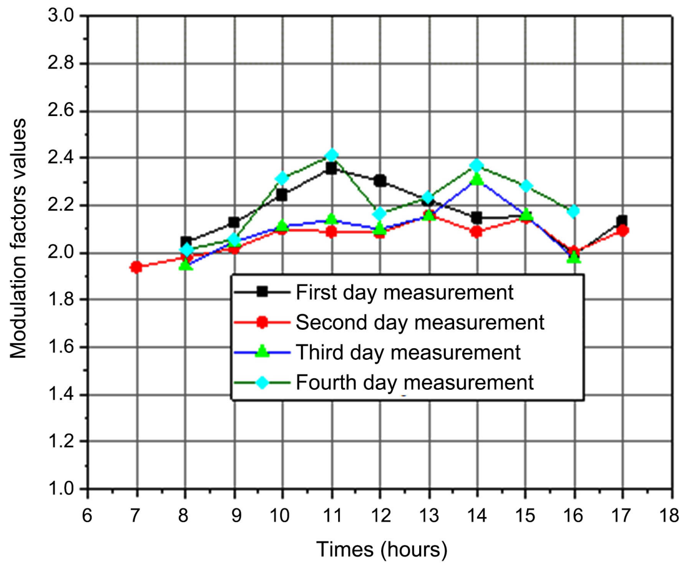

Figure 13. Oscillation curves of the modulation factor during the four days.

This range of variation of the index satisfies the condition for transferring power to the distribution network for all PV production values. For amplitude modulation factor less than these values, the level usage in odd-level inverters can be sufficiently rotated so that the switching frequency can be doubled and still keep the thermal losses within the limits of the devices [3]. The rise in the modulation factor has the effect of pushing the output voltage harmonics towards the frequencies of higher order, which facilitates their filtering by the inductance.

The inverters used have an input voltage range between 125 V and 400 V. Based on the grid parameters, the inverter controls the PV production while ensuring the search for the Maximum Power Point (MPPT) [14]. These obtained results show a device in good working order at the technical level and able to operate correctly in order to ensure its main function of power transfer. In general point of view, this analysis gives full satisfaction.

Figures 14(a)-(d) show the daily variation of the inverter output voltage and the phase angle. We observe undulations with distortions on the different obtained curves due to the sudden switching of the inverter output voltage. These non-sinusoidal voltages are considered to be the vector sum of a voltage at a frequency of 50 Hz (desired voltage) and voltages of multiple frequencies of 50 Hz (unwanted voltage). Indeed, these harmonic voltages cause the circulation of disturbing harmonic currents. This confirms the analysis made in reference [14] relating to the choice of inverters. The observed discontinuities are also mainly due to the momentary shutdowns of the inverters. To limit these harmonics, it is advisable to manage the transistors of the inverter according to the principle of control by pulse width modulation *i.e.*, the duration of the conduction of the transistors is all the longer as the instantaneous value of the voltage is high (**Figure 7**). It emerges from this analysis that the two parameters thus simulated are very important to control in order to orientate the transfer of the power flow from the continuous cell to the alternating part.

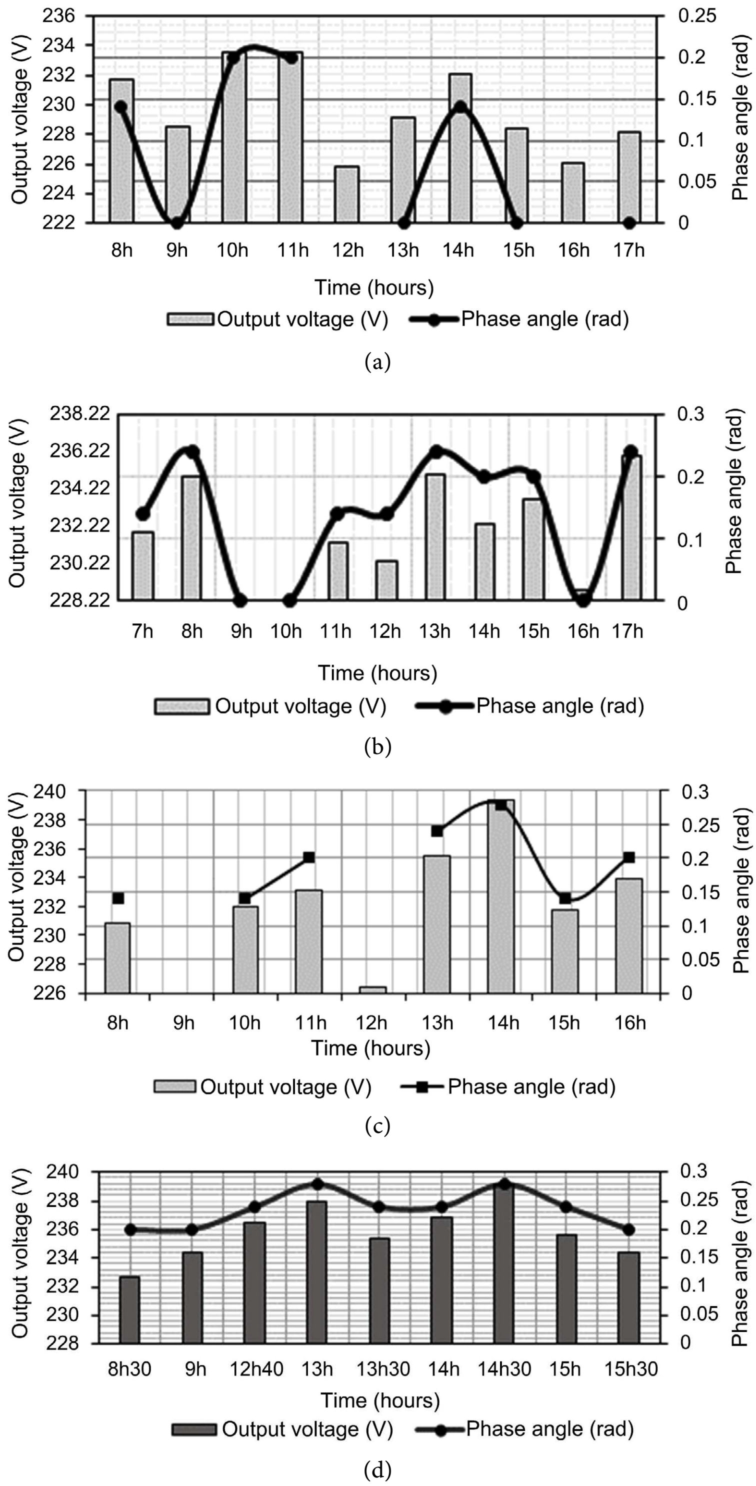

Figure 14. (a) Inverter output voltage variation and phase angle (first day); (b) Inverter output voltage variation and phase angle (second day); (c) Inverter output voltage variation and phase angle (third day); (d) Inverter output voltage variation and phase angle (fourth day).

After a detailed study, to implement this proposed device, we must have modular cards with distinct functions in the control part and the power part (see

Figure 6).

The power stage consists of six (06) transistors (see **Figure 8**). The transistors Q_1, Q_2 and Q_5 form the first power stage. The transistors Q_1, Q_2 are fixed on the card placed at the input of the first stage and Q_5 on the card placed at the output of the stage.

The transistors Q_3, Q_4 and Q_6 constitute the second power stage. Likewise, Q_3, Q_4 are fixed on the card placed at the input of the second power stage and Q_6 on the card placed at the output of the stage. The two power stages are interconnected by means of output transformers. The combination of these two forms the power stage of the inverter.

7. Conclusion

In this research paper, a design approach has been proposed, where the design parameters of a DC/AC inverter in PV connected to the grid system are calculated and analyzed. Mathematical equations based on the current-voltage characteristics of the inverter have been developed. The simulation model was validated using experimental data from a 25.2 kWp grid-coupled photovoltaic (PV) system, connected to Gridfit type inverters. The data were exported and implemented in programming software. A good agreement was observed and this shows all the robustness and the technical performances of the energy converter device. Simulated and field-testing results also are shown that increases in the value of the modulation factor (m) for low power output are highly significant. A short presentation of the design model of the inverter has been proposed in this article. An implementation of the inverter will be very soon associated with an experimentation station.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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