Journal of Engineering Science and Technology Review 17 (6) (2024) 132-139

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Optimal Approach to Photovoltaic Electricity Injection in an Unstable Grid: Case Study

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Received 22 January 2024; Accepted 13 October 2024

Abstract

The injection of photovoltaic electricity into the distribution grid has harmful impacts on the electrical grid which limits this injection and causes the malfunction of the electrical grid. This is why it is necessary to seek the optimal power of photovoltaic electricity to be injected into the interconnected grid already unstable. The site considered for this study is the 33 MW photovoltaic power plant of Zagtouli which must inject its electricity production into the national interconnected grid of Burkina Faso, from the Zagtouli substation located in Ouagadougou. In the NEPLAN software, the scenario adopted consisted in varying the power of the photovoltaic electricity injected at the injection point of the Zagtouli substation until an overload of one or more elements of the network was observed. The simulation results showed that the maximum power of photovoltaic electricity that can be injected at the Zagtouli substation is 20 MW and those, without regulating the voltage of the unstable network. For photovoltaic powers between 20 MW and 70 MW, voltage and active power regulation are necessary. The results of this study can be used to optimize the injection of electricity from photovoltaic power plants into the interconnected national electricity grids of West African countries, which are experiencing the same instability problems as the national interconnected network of Burkina Faso.

Keywords: PV plant, electricity, unstable grid, optimal injection

1. Introduction

In developing countries, the demand for electricity is growing more and more, in particular due to demographic changes and the development of certain geographical areas. For a number of years, West African countries have been plunged into a major energy crisis marked by grid outages and load shedding. In this context, it is essential to resort to the production of electricity from renewable sources. Because of the enormous solar potential of this sub-region, the establishment and integration of photovoltaic power plants in national electricity grids are prioritized to deal with this energy crisis. Major photovoltaic electricity injection projects are planned to improve the supply of access to electrical energy [1].

In West Africa, many large-capacity photovoltaic solar projects with injection into national electrical grids have been carried out. This is the case of the 6.5 MWp photovoltaic power plant of Praia in Cape Verde [2], the 33 MWp photovoltaic power plant of Zagtouli at Ouagadougou in Burkina Faso. In Togo, it is a photovoltaic solar power plant with a power of 50 MWp, installed in the city of Blitta and connected to the national electrical grid. Other photovoltaic power plants are ongoing construction, such as the Awandjélo solar power plant. With a power of 42 MWp, this installation will be connected to the national electrical grid of Togo.

However, the injection of electricity from a photovoltaic power plant into the distribution network can have impacts on the electricity network [3-4]. In addition, the characteristics and disturbances of the distribution network can influence the operation of the photovoltaic power plant [5-6]. The injection of photovoltaic electricity causes a local rise in the voltage at the injection point. This problem was tested by Hadj Arab et al. [7]. Even with low injected power, they noticed that the voltage at the injection point was high. According to Thi Minh Chau Le, during a period of strong sunshine and low consumption, the injection of photovoltaic electricity creates an overvoltage at the injection points. The voltage of some nodes of the network can exceed the admissible threshold which causes the decoupling of the photovoltaic power plant [8-9]. Another consequence of the injection of photovoltaic electricity is the pollution of the electrical network by harmonics. It generates harmonics that disturb the voltage waveform [10]. When this is not sinusoidal, there will be a malfunction and overheating of the receivers and equipment connected to the network [11]. The injection points of photovoltaic power plants are located at the level of the distribution network [12]. However, the distribution network is designed to transport power flows from the source substation to the consumers. Sometimes production exceeds consumption, which creates an upward flow of active power [13-14]. If the photovoltaic electricity injection rate is high enough, the energy flows from the distribution network to the transmission network, which causes local congestion. According to ZERKOUT et al. [15], the multiplication of photovoltaic injections into the network is one of the reasons for the increase in the number of congestions [16]. The injection of photovoltaic electricity causes the imbalance

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ISSN: 1791-2377
doi:10.25103/jestr.176.16

between phases [17]. In the case of the use of single-phase inverters, an imbalance between phases appears, because the power produced is not correctly distributed between the three (3) phases of the same three-phase photovoltaic system. This leads to an imbalance in the electrical grid [18].

An unsuitable coupling between photovoltaic power plants and the electricity grid can lead to a low level of reliability and poor quality of the network. It is therefore necessary to develop analytical tools and carry out in-depth studies of the interactions between photovoltaic plants and the grid [19-20]. The challenge of injecting photovoltaic electricity into public networks lies not only in the optimized management of this injection, but above all in the impact of the injection in terms of disruption of the network, which is already unstable. The problem is how to manage an intermittent resource injected into a network itself unstable, characteristics of African networks.

It is therefore essential to seek models for the optimal injection of photovoltaic power plants power into these interconnected networks [21].

In Burkina Faso, located in West Africa, where this study is taking place, the ambition is to inject nearly 650 MW into its electricity grid by 2030 [22]. Currently, the electricity production of three photovoltaic power plants is injected into the national interconnected electricity grid, namely photovoltaic power plant of Zagtouli with a peak power of 33 MW ; Ziga photovoltaic power plant with a peak power of 1.1 MW and Nagréongo photovoltaic power plant with a peak power of 26 MW, ie a total power of 60.1 MW injected at this moment, which represents only about 9% of the planned power.

This work concerns the optimization of electricity injection from the 33 MW photovoltaic power plant of Zagtouli located in Ouagadougou, Burkina Faso. At the peak of its production, the Zagtouli plant was only able to inject 18 MW. The injection of photovoltaic electricity from this plant into the distribution network of the Burkinabè national electricity company causes enormous problems which do not allow the optimal injection of photovoltaic electricity into the interconnected electricity grid [23-24].

This study will not only focus on the maximum capacity of the injection point like previous research, but will highlight the impact of this injection on the grid, in particular the variation in voltage and the contribution of the balance node; i.e. the interconnection with Ghana.

The main objective of this study is to find the maximum power of photovoltaic electricity from the 33 MW photovoltaic power plant that can be injected at the injection point of the Zagtouli substation, without causing a major fault on the whole of the national interconnected grid (NIG).

2. Studied site presentation

The studied site is that of the 33 MW photovoltaic solar power plant of Zagtouli, located at Ouagadougou in Burkina Faso, West Africa. Ouagadougou is the political capital of Burkina Faso. Its area is 520 km^2, with an estimated population of 2.8 million in 2022. The city of Ouagadougou is the largest urban center in the country.

The 33 MW Zagtouli photovoltaic power plant is located in the suburbs of Ouagadougou. The site, property of the national electricity distribution company is 14 km west of Ouagadougou and 1 km south of the National Road number 1. The Figure 1 shows the geographical location of the photovoltaic power plant of Zagtouli in Ouagadougou.

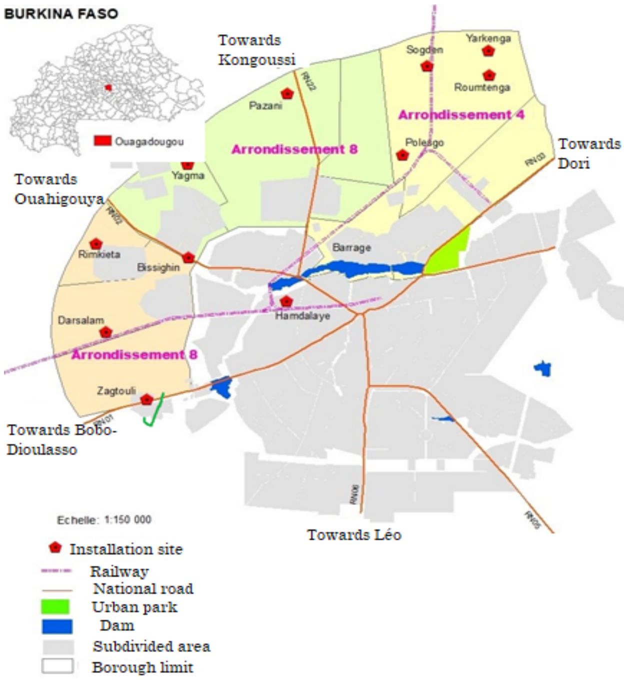

Fig. 1. Geographical location of the Zagtouli photovoltaic power plant.

Figure 2 presents the spatial occupation of the Zagtouli power plant [25].


Fig. 2. Spatial occupation of the photovoltaic field of the PV plant [17].

The plant has 129,600 photovoltaic modules of 260 Wp each in polycrystalline silicon, mounted on 1,800 structures inclined at 15° and facing south, over an area of 60 hectares. The total peak power of the photovoltaic power plant is 33 MW. The power plant's electricity is produced without storage and injection takes place at the Zagtouli substation on the 33 kV busbar. Figure 3 shows the injection point of the 33 MW Zagtouli photovoltaic power plant.

The regulation of the voltage at the injection node is carried out by the set of switchings of the two reactances of 15 MVAR and 30 MVAR locally from the station or remotely from the dispatching in a manual or automatic way.

This plant is of modular configuration and comprises sixteen transformer stations. Each substation includes one transformer (420 V / 33 kV) and two inverters (270 VDC / 420 VAC). All the elements of each station are housed in a building called the Integrated Photovoltaic Center (CPI). The service life of the plant is at least 30 years.

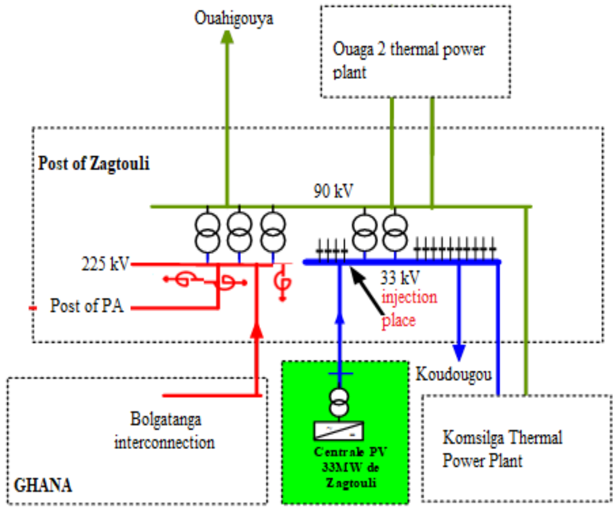

Fig. 3. Injection point of the Zagtouli power plant [17].

3. Materials and Method

The scenario consists of varying the power of the photovoltaic electricity injected at the injection point of the Zagtouli substation, up to the convergence limit, i.e. until an overload of one or more elements of the grid is observed. It is necessary to model the national interconnected network and then simulate the injection of photovoltaic electricity into the grid using a simulation tool. The simulation mode will permit to determine the maximum power of the photovoltaic electricity to be injected into the interconnected electrical grid seen from the city of Ouagadougou, taking into account the constraints of the involved grid in relation to static security.

There are several simulation tools in the form of software or simulator. There are simulators for distribution and/or transportation networks. Real-time simulators include OPAL-RT Technology, hypersim, etc. Existing software is that of static and/or dynamic simulation in real time and offline. In the offline simulation software group, there are EUROSTAG, PSS/E (Power System Simulator for Engineering), dIgsilent power factory (Digital Simulation and Electrical NeTworks), NEPLAN, etc.

Our study having the objective of determining the maximum power in the electrical network, the type of simulation is static simulation in delayed time. The NEPLAN software is free for up to 50 nodes and meets pre-established criteria. The modeling of the interconnected network seen from Ouagadougou and the simulation of the injection of electricity into the network in this study are carried out with the NEPLAN modeling and simulation software.

3.1 NEPLAN software presentation

Version 5 of the NEPLAN software is a tool used in planning and information systems for electricity, gas, water supply grids, as well as heating grids [26]. All the basic components of the electrical grid in NEPLAN are represented in the structure figure 4.

An element corresponds to a component of the grid, such as a line, a transformer or an electrical machine. There are active and passive elements. An element is conceptually described by a starting node and an ending node. For three-winding transformers, a third node must be given. The elements are electrically described by the nominal current, the nominal power, the nominal voltage, parameters such as losses, reactances, etc.

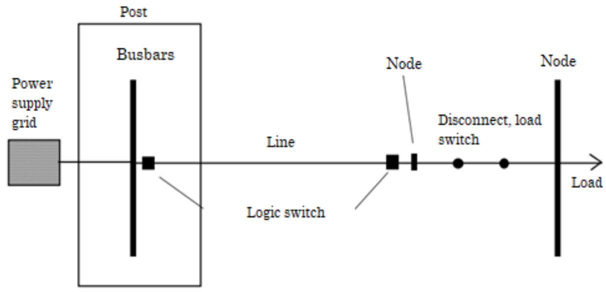

Fig. 4. Electrical grid components representation in NEPLAN software.

In NEPLAN, parameters are entered using an input data mask. The active elements are the supply grids, the asynchronous and synchronous machines, as well as the supply stations or groups. A feeder grid represents a neighbor grid. Passive elements are lines, coupling elements, breaking elements, 2 and 3 winding transformers, shunts and loads. Loads can be entered along a line without the need to enter a node (line loads).

The NEPLAN software allows simulation in static and dynamic regimes. The calculation method used in NEPLAN is that of Newton Raphson, which uses the principle of iteration. This method consists in the use of an algorithm for the resolution of equation by successive approximations. The working process of the algorithm is based on convergence. The calculation converges when the equation to be solved has a solution.

3.2 Grid modeling

The simulation of the injection of photovoltaic electricity on the interconnected grid seen from the city of Ouagadougou, involves modeling the interconnected electrical grid seen from the city of Ouagadougou. Modeling of the interconnected grid takes into account loads, transformers, generators, lines and busbars [27].

The methodology considered to assess these powers is as follows: inventory of the load equipment of the interconnected grid seen from the city of Ouagadougou; inventory of load equipment attached to the interconnected grid seen from the city of Ouagadougou ; aggregation of powers connected to the node.

Active elements are modeled using their sub-transient reactance. For a power distribution calculation, these elements are modeled by their active and reactive powers or by the magnitude and angle of a voltage at the designated node. The data collected on the entire grid will allow to find the powers connected to each node of the grid. The active power connected to node i is calculated according to relation (1).

$$P_i = \sum_{j=1}^{m} \left(\sum_{k=1}^{n} p_k \right) k_{uk} k_{sk} \qquad (1)$$

where:

- P_i is the active power connected to node *i (W)*,
- p_k, k_{uk}, k_{sk} are respectively the power, the utilization factor and the simultaneity factor of the household *k*,
- m is the number of plots connected to the node,
- n is the number households in plot *j*.

The reactive power connected to node i is calculated according to relation (2).

$$Q_i = P_i \tan \varphi \qquad (2)$$

where:

- Qi is reactive power (MVAr)
- P_i is the active power connected to node i,
- Q_i is the reactive power connected to node i,
- φ is the phase shift.

In addition to nodes there are lines and transformers. The lines are characterized by type, length, current capacity, linear resistance, linear reactance and linear capacity. As for transformers, they are defined by apparent power, iron losses, primary voltage, secondary voltage, short-circuit voltage. The voltage variation at the injection station is given by relation (3).

$$\Delta\% = \frac{(Udisp - Usim)*100}{Udisp} \quad (3)$$

where:

- $\Delta\%$ is the voltage variation at the injection station,
- U_{disp} is the voltage given by dispatching,
- U_{sim} is the voltage resulting from model simulations.

The average variation is given by relation (4).

$$\Delta_{av}\% = \frac{\left(\sum \Delta\%\right)\times 100}{N} \quad (4)$$

where:

- $\Delta_{moy}\%$ is the average variation,
- $\Delta\%$ is the voltage variation at the injection station,
- N is the number of measurement points.

After the grid model seen from Ouagadougou, it is essential to check the validity of the model.

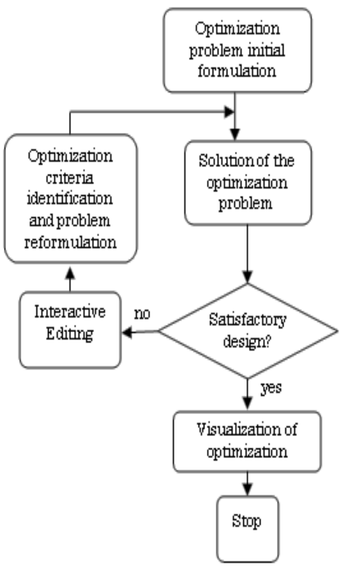

Fig. 5. Steps for solving an optimization problem.

3.3 Simulation injection of photovoltaic electricity

The optimization of the injection consists in determining the maximum power to be injected beyond which serious disturbances can occur on the electrical grid. The constraints linked to the optimization of the injection are such that the voltage of the grid must remain within the contractual limits, the frequency of the grid must remain within the contractual limits, the total energy in the lines must be at most equal to the capacity of this, the powers supplied by the generators and the transformers must be within the nominal limits. The diagram in figure 5 defines the steps in the optimization of a given problem.

4. Results and Discussions

4.1 Modeling of the interconnected grid seen from Ouagadougou

The interconnected electricity grid of Ouagadougou city consists of seven (07) power stations, namely Zagtouli, Komsilga, Ouaga 1, Ouaga 2, Kossodo, Patte d'Oie and Ouaga 2000. In addition to being interconnection stations, Ouaga 1, Ouaga 2, Kossodo and Komsilga are thermal power plants and Zagtouli benefits from a photovoltaic power plant and two 225 kV lines from Côte d'Ivoire and Ghana. Energy exchanges with the rest of the country take place through the substations of Zagtouli, Patte d'Oie and Kossodo. Figure 6 represents the structure of the electricity grid of Ouagadougou city.

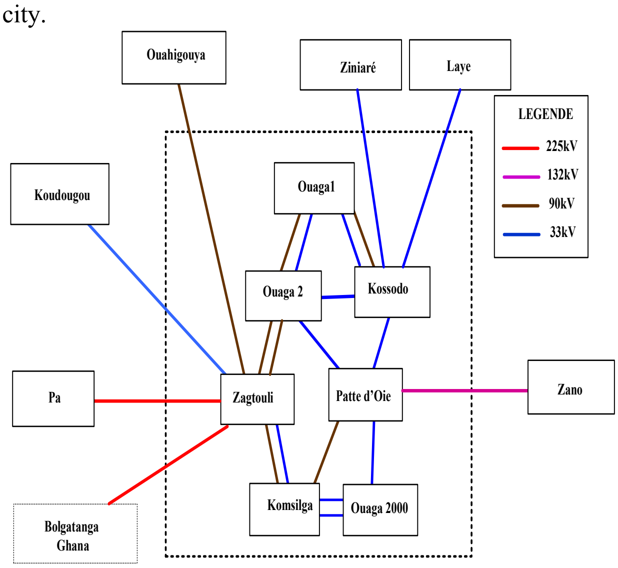

Fig. 6. Structure of the interconnected electrical grid of Ouagadougou city.

Table 1 represents the values resulting from the dispatching and those from the simulation of the model. To allow an exhaustive evaluation of the results, all the nodes are considered.

Table 1. Node voltage characteristics from model simulations

Posts	Nods				
	Number	landmark	Nominal voltage (kV)	Simulation voltage	
				(kV)	(%)
Zagtouli	1	JDB_225kV_Zagtouli	225	225	100
	2	JDB_90kV_Zagtouli	90	92,5	102,8
	3	JDB_33kV_Zagtouli	33	34,6	104,8

Table 2 presents the node voltages obtained from dispatching and model simulations.

Table 2. Characteristics of dispatching node voltages and from simulations

Designation JDB	JDB number	Dispatching volage (%)	Model voltage (%)
JDB_225kV_Zagtouli	1	100,6	100
JDB_90kV_Zagtouli	2	104,5	102,8
JDB_33kV_Zagtouli	3	104,6	104,8

Figure 7 shows the model structure of the interconnected electrical grid, seen from Ouagadougou city.

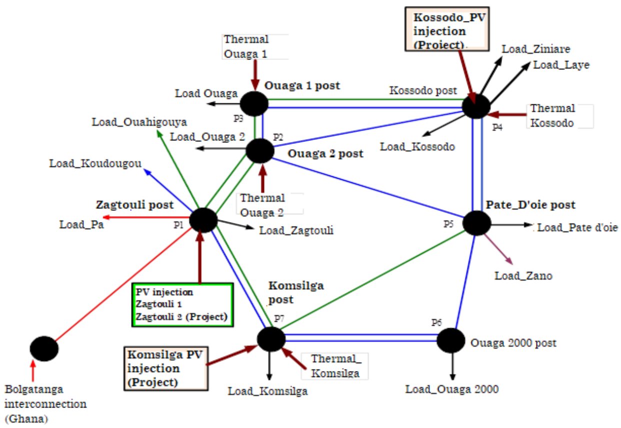

Fig. 7. Structure of the electrical grid model seen from Ouagadougou city.

In Figure 7, point P1 is a measurement point at the Zagtouli substation which includes three busbars of 225 kV, 90 kV and 33 kV. This point has 3 nodes: N1, N2 and N3; point P2 is a measurement point at the Ouaga 2 substation which includes three busbars of 90 kV, 33 kV and 15 kV. This point has 3 nodes: N4, N5 and N6); point P3 is a measurement point at the Ouaga 1 substation which includes two busbars of 90 kV and 15 kV. This point has 2 nodes: N7 and N8; P4 is a measurement point at the Kossodo substation which includes five busbars of 90 kV, two of 33 kV and two of 15 kV. This point has 5 nodes: N9, N10, N11, N12 and N13; point P5 is a measurement point at the Patte d'Oie substation which includes four busbars of 132 kV, 33 kV and two 15 kV. This point has 4 nodes: N14, N15, N16 and N17; point P6 is a measurement point at the Ouaga 2000 substation which includes two busbars, 33 kV and 15 kV. This point has 2 nodes: N18 and N19; point P7 is a measurement point at the Komsilga substation which includes three voltage levels: 90 kV, 33 kV and 15 kV. This point has 3 nodes: N20, N21 and N22.

The model thus defined has a total of twenty-two (22) nodes. The electrical grid studied being connected to the national electrical grid, the modeling of the latter must take into account the external lines attached to it. These lines are those of Zano (Load_Zano), Ouahigouya (Load_Ouahigouya), Koudougou (Load_Koudougou, Pa (Load_Pa) and that of Bolgatanga coming from Ghana.

4.2 Model validity

The validity of the model is dependent on the results conformity of the model simulation with respect to the state of the grid according to the peak of 18 MW on the date of 04/15/2022. To this end, the characteristics of the loads are introduced and simulations are carried out in such a way as to obtain values of the voltages of the nodes which are identical or close to those received from dispatching. All network nodes are considered in the validity of the model, ie twenty-two (22) nodes.

The conformity of the characteristics resulting from the simulations of the model with those of the dispatching is evaluated by a calculation of the relative variation between these quantities. The results are recorded in Table 3.

Table 3. Model and dispatch voltage values

Voltage from dispatching (%)	Voltage from model (%)	Variation (%)
10.6	99 .6	1.0
104.5	102.3	2.1
104.6	104.8	-0.2
103.0	101.6	1.4
99.2	104.1	-4.9
104.2	105.8	-1.5
102.7	101.6	1.1
103.5	103.4	0.1
102.1	101.5	0.6
99.7	101.4	-1.7
99.7	101.3	-1.6
104.4	101.7	2.6
104.5	102.8	1.6
99.9	102.10	-2.2
97.6	101.6	-4.1
102.3	104	-1.7
101.7	104	-2.3
98.8	100.2	-1.4
101.9	103.7	-1.8
104	102.6	1.3
101.5	103	-1.5
101.7	103	-1.3

The maximum relative variation between the magnitudes of the model voltage and those of the dispatching is 4%. The average of less than 1% or precisely 0.6%. These values being relatively low, the model therefore reflects the reality of the electrical grid of the city of Ouagadougou or the national electrical grid seen from Ouagadougou.

4.3 Injection simulation results

The results obtained after simulation of the injection at the Zagtouli substation, up to the convergence limit are presented. In Table 4, the injected photovoltaic electricity power, variation of the substation voltage and the transmission angle on the line coming from Ghana are represented.

When there is no PV power injected at the Zagtouli substation, the voltage variation compared to the nominal voltage ranges from 92% at the Patte_Oie substation to 98.6% at the Zagtouli substation. For the injection of photovoltaic power at the Zagtouli substation, the maximum allowable photovoltaic electricity power at the injection point is 70 MW. When the injected power exceeds 70 MW, the two 90 MW / 33 kV transformers operate respectively at more than 80% and in the event of loss of the Koudougou line, they go to 104% each. The transport angle varies between -20.6° to 10.2°. The permissible limiting angle is 20°.

Table 4. Voltage variation in substations

PV power injected (MW)	Voltage variation (%)							Angle (°)
	Substations							
	Zagtouli	**Kossodo**	**Komsilga**	**Ouaga2**	**Ouaga1**	**PatteOie**	**Ouaga2000**	
0	98,6	96,9	97	97,4	97	92	92,7	10,2
18	104,8	104,6	103,8	105	103,7	100,4	100,4	-0,9
20	105,17	105	104,2	105,4	104,1	100,9	100,8	-1,7
30	106,7	106,9	105,8	107,1	105,8	102,8	102,7	-5,8
40	107,6	107,9	106,8	108	106,7	103,9	103,8	-9,1
50	108,5	108,9	106,5	109	107,7	105	104,9	-12,7
60	109,2	109,9	108,6	109,9	108,5	106	105,8	-16,6
70	109,7	110,6	109,2	110,6	109,1	106,8	106,5	-20,6

Figure 8 shows the variation curves (%) of the node voltage as a function of the injected PV power (W) into the Zagtouli substation.

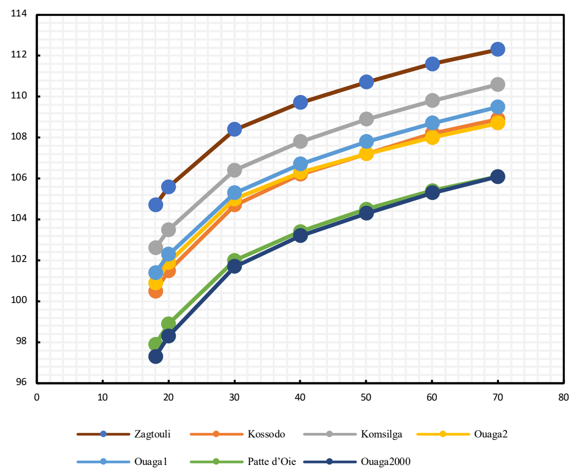

Fig. 8 Variation curves (%) of the node voltage as a function of the injected PV power (W) - Zagtouli substation

As peak consumption in 2022, the Zagtouli photovoltaic plant injected 18 MW. From the curves plotted in Figure 8, the observation is that when the injected power decreases, the voltages of the nodes decrease. On the other hand, when the power of photovoltaic electricity increases, the voltage at the nodes evolves in the same direction. PV injection at the Zagtouli substation has a maximum power of 70 MW. When the injected power into the Zagtouli substation increases from 18 MW to 70 MW, the voltage varies from 104.9% to 112.6% at Zagtouli substation, from 102.9% to 110.9% at Komsilga substation, from 109.8% to 101.9% at Ouaga1 substation, from 100.9% to 108.9% at Kossodo substation, from 101% to 108.9% at Ouaga2 substation, from 98% to 106.2% at Patte_Oie substation and from 97.9% to 106.2% at Ouaga2000 substation.

The variation in grid voltage is then from 92% to 100%, i.e. a drop of 8% in the nominal voltage (Un).
The operating constraints of the grid being ±5% of the nominal voltage in N safety and ±10% in N-1, PV injection at the Zagtouli substation requires voltage regulation at the injection point.

Figure 9 shows the evolution of the transmission angle according to the photovoltaic power injected into the interconnected grid at the Zagtouli substation in Ouagadougou.

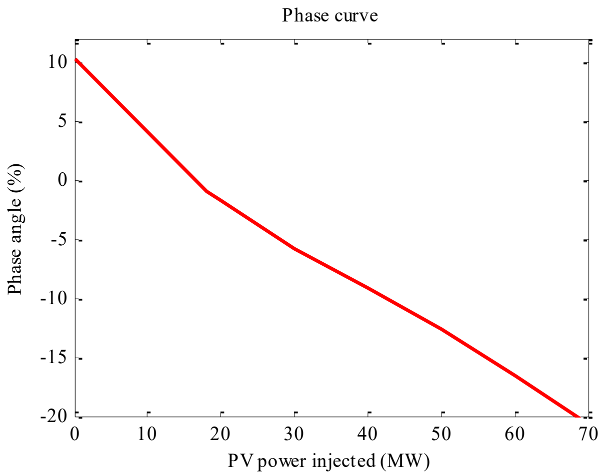

Fig. 9. Transport angle variation.

The transport angle, i.e. the phase difference between the voltage and the current of the interconnection line with Ghana which constitutes the pendulum node varies in absolute value between 10.2° and 20.6° (Figure 9). The grid operating constraints being ± 5% of the nominal voltage in safety N and ± 10% in N-1, the transport angle of 20°.

The implementation of photovoltaic injection at the Zagtouli substation requires voltage regulation at the injection point. The intermittency of production is effectively modulated by the interconnection with Ghana.

4. Conclusion

The main objective of this study is to find the maximum power of photovoltaic electricity to be injected into the unstable interconnected electrical grid without causing a major fault in the grid. The considered site for this study is the 33 MW photovoltaic power plant of Zagtouli which must inject its electricity production into the national interconnected grid (NIG) from Ouagadougou.

In the NEPLAN software, the scenario adopted consisted in varying the power of the photovoltaic electricity injected at the injection point of the Zagtouli substation until an overload of one or more elements of the grid was observed.

The simulation results showed that the maximum power of photovoltaic electricity that can be injected at the Zagtouli substation is 20 MW and those, without regulating the voltage of the unstable grid. Any injection of photovoltaic electricity into the interconnected grid from Ouagadougou whose power does not exceed 20 MW, the self-regulation of the electricity grid is sufficient to contain the voltage of the nodes within admissible proportions. For photovoltaic powers between 20 MW and 70 MW, voltage and active power regulation are necessary. Beyond 70 MW a need to reorganize the electrical grid is necessary.

The injection of photovoltaic electricity into the grid generates as many static problems. It causes the voltage to increase at the injection point and throughout the grid. The injection of photovoltaic electricity also generates dynamic instability. It causes an inadmissible variation of the power of the pendulum node.

This study highlighted the impact of the injection of PV production on the network, in particular the variation in voltage between 92 and 110% and the contribution of the balance node, which represents the compensating power for the intermittency of PV production. (-142 and -91 MW) or a variation of 51 MW. In the case where it is the interconnections which provide this compensation, it is necessary to provide an equivalent power reserve to support the grid, if an interconnection failure occurs.

On an economic level, the optimization of PV injection on the interconnected national grid will make it possible to reduce the cost of electricity by up to 0.102 $ per kWh.

From an environmental perspective, PV injection is an alternative to the use of Heavy Fuel Oil (HFO) and Diesel Distillated Oil (DDO), which are very polluting.

From the structure of the interconnected national grids of each country (Figure 6), the model of each region can be developed like that of figure 7.

The results of this study can be used to optimize the injection of electricity from photovoltaic power plants into the interconnected national electricity grids of West African countries, which are experiencing the same instability problems as the national interconnected grid of Burkina Faso.

Acknowledgements
The authors want to thank the Regional Center of Excellence for Electricity Control (CERME) of University of Lomé, The Norbert Zongo University of Koudougou, the Nazi Boni University of Bobo-Dioulasso and the National Center for Scientific and Technological Research for providing an enabling environment during the research.

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