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Study of the Impact of Grid Disconnections on the Production of a Photovoltaic Solar Power Plant: Case of Diamniadio Power Plant

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Abstract

Today, renewable energy projects connected to the interconnected network, with powers of the order of tens of megawatts, are more and more numerous in sub-Saharan Africa. And financing these investments requires a reliable amortization schedule. In the context of photovoltaic systems connected to the interconnected electricity grid, the quintessence of damping is the amount of energy injected into the grid. Thus it is fundamental to know the parameters of this network and their variation. This paper presents an evaluation of the impact of power grid disturbances on the performance of a solar PV plant under real conditions. The CICAD photovoltaic solar plant, connected to the Senelec distribution network, with an installed capacity of 2 MWp is the study setting. An energy audit of the plant is carried out. Then the percentage of each loss is determined: voltage drops, module degradation, inverter efficiency. The duration of each disconnection is measured and recorded daily. The corresponding quantity of lost energy is thus calculated from meteorological data (irradiation, temperature, wind speed, illumination) recorded by the measurement unit in one-minute steps. The observation period is three months. The total duration of disconnections related to the instability of the electrical network during the study period is 46.7 hours. The amount of energy lost is estimated at 22.6 MWh. This represents 2.4% of the actual calculated production.

Keywords

Photovoltaic Power Plant, Disconnections, Network, Evaluation, Lost Energy

1. Introduction

Photovoltaic (PV) solar energy, having the sun as its primary source, is very appropriate for the production of electrical energy in some countries such as Senegal with a high solar potential (varying between 1850 and 2250 kWh/m^2/year [1]). It also has the advantage of simplicity of installation and commissioning, compared to other renewable energy plants. Senegal inaugurated in 2014, with the CICAD plant (2 MWp) its first PV plant connected to the 30 kV distribution grid.

Since 2016, an acceleration in the commissioning of PV plants has been noted. With the connection and injection of: Bokhol (20 MWp), Malicounda (22 MWp), Kahone (20 MWp), Ten Merina (29.5 MWp), Santhiou Mekhe (29.5 MWp), Sakal (20 MWp) and Diass (20 MWp in test phase), the PV power connected to the Senelec interconnected grid has increased from 2 MWp to 164 MWp between 2016 and 2019 [2]. However, various studies show the impacts of PV power plants on the grid such as: local voltage rise at the connection point [3], voltage bumps [4], rapid power variations [5]… But this connection imposes grid stability conditions that are not always guaranteed. This leads to disconnections of the inverters followed by energy loss during the period of grid instability. Depending on the output of the PV plant, the decoupling function can be internal or external to the inverter. The decoupling function is integrated in the inverter for small power sources, equipped with an inverter of less than 5 kVA. It is accepted that this decoupling protection function is provided by an automatic disconnector. Today, only the German standard DIN VDE 0126 is recognized. Two independent devices are connected in series, each with a disconnecting device for maximum safety. This device constantly monitors the quality of the grid by measuring voltage, frequency and impedance [6]. The decoupling function is external to the inverter for installations with a power rating of more than 5 kVA. The decoupling protection function is then provided by measuring relays that are independent of the inverter. Three types of protection are currently recognized for photovoltaic generators (GPV) connected to the public low voltage distribution grid [7]. The general objective of this work is to evaluate the performance of solar PV plants based on the impact of grid stability. This is a novelty in the field because most publications deal with the impact of intermittency on the interconnected grid.

Thus, based on the meteorological data and the energy produced by the plant, recorded over a period of three months, we will evaluate the losses due to the grid.

In this document, we first present the CICAD solar power plant as well as the methodological approach adopted. Then, the evaluation of the amount of energy lost as well as the corresponding duration will be presented in the results and discussion section.

2. Methodology

Based on the daily reports from the Abdou Diouf International Conference Center (CICAD) power plant, the meteorological data recorded and additional physical measurements carried out in the PV field, all the losses, the number and duration of interruptions as well as the quantity of energy produced day by day are aggregated. The working method adopted, consists in first making an energy audit of the plant in order to identify all the existing losses. Then determine the percentage of each type of loss on production. Finally, the total duration of the disconnections and the corresponding amount of energy during the study period are evaluated.

2.1. Presentation of the CICAD Plant

The Centre International de Conference Abdou Diouf (CICAD) Solar PV power plant is the first PV power plant interconnected to the Senelec power grid. It is located in Diamniadio (30 Km from Dakar **Figure 1**) and was commissioned in November 2014. The plant with a total installed capacity of 2 MWp, is connected to the 30 kV distribution grid through a 2 kVA, 30/400kV transformer.

The CICAD plant is composed mainly of the following elements:

- A photovoltaic field.
- 116 boxes or junction boxes.
- Fuse grouping boards.
- Two inverters branded GAMESA of 1 MW each.
- A 2 kVA transformer.
- Cables.
- Parameter monitoring system (SCADA).
- Protection equipment.
- A meteorological station.

Table 1 summarizes the description of the plant. The technical characteristics of the modules used are given in **Table 2**.

Table 3 shows the recommendations for decoupling protection according to the German standard DIN VDE 0126.

Table 4 shows the technical specifications of the GAMESA E1 inverter, given by the manufacturer. The inverter acts as a DC-AC converter. This allows the energy produced by the PV field to be injected into the public electricity distribution grid. It also integrates coupling-decoupling functions as well as maximum and minimum protection of electrical parameters (voltage and frequency).

2.2. Different Causes of Performance Degradation

The performance of a PV plant decreases over time due to a degradation process of the PV system, especially the PV panels. Also, the inverters, transformer, connectors, and protection system can be affected by degradation [9]. **Table 5** shows all the detected degradations as well as the causes and consequences.

2.3. Assessment of Plant Losses

The evaluation of the system losses of the power plant is necessary to control the amortization plan and the follow-up evaluation of the investment. It also allows to evaluate the quality of the Senelec distribution grid in the area.

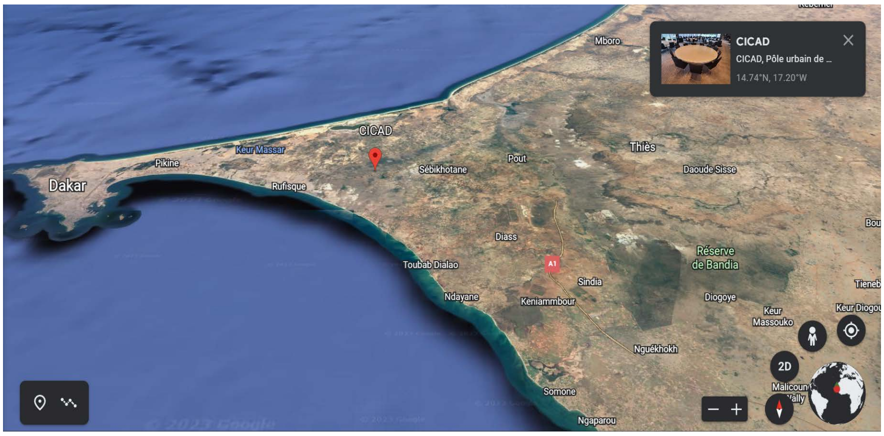

Figure 1. Geolocation of the CICAD site.

Table 1. Description of the CICAD plant.

Site Name	CICAD solar plant
Area	2.2 hectares
Number of modules YL295P-35b	6960
Coordinates	14˚33'44"North, 16˚47'13"West, Elevation: 0 m
Tilt Azimut	6˚
South orientation	24˚

Table 2. Technical specifications of the module operated at the CICAD plant.

Sizes	Values
Nominale power (P)	295 W
Optimal voltage (Vopt)	35.6 V
optimal Current (Iopt)	8.29 A
Open circuit voltage (Voc)	45 V
Current short-circuit (Isc)	8.99 V
Reference temoerature	25˚C

Table 3. Types of decoupling protection in BT.

BT decoupling protections	Type B.1 (ex type 2.1)	Type B.2 (ex type 2.2)	Automatic disconnector DIN VDE 0126
Detection of HTA single-phase faults	Not done	Note done	Note done
Detection of BT polyphase faults	Minimum instantaneous V 85% Vn	Minimum instantaneous V 85% V_n	Minimum instantaneous V 80% V_n
Separate grid operation	Minimum instantaneous V 85% V_n	Minimum instantaneous V 85% V_n	Minimum instantaneous V 80% V_n
	Maximum instantaneous V 115% V_n	Maximum instantaneous V 115% V_n	Maximum instantaneous V 115% V_n
	Minimum of f instantaneous 49.5 HZ		Minimum of f instantaneous 49.8 HZ
	Maximum instantaneous f 50.5 HZ		Maximum instantaneous f 50.2 HZ

Table 4. Technical specifications of the inverter [8].

DC Input Values	
Recommended rated power	1200 kWp
Max. Direct Current	1800 A
Direct Current Voltage range	570 - 1000 V
DC MPPT Voltage range	570 - 910 V
No. Of DC Inputs	12
Start of production	0.5% Pn approx.
AC output values	
No. of phases	3
Rated AC power	1000 kW
Maximum AC power	1100 kW
Rated AC voltage	360 Vrms
AC voltage range	−15%/+10%
Output frequency range	47.5…53/57…63 Hz

Table 5. Summary of the main sources of plant performance degradation.

Degradation type	**Cause**	**Consequence**
Corrosion	Moisture Penetration	Increased leakage current performance loss
Delamination	Loss of adhesion between the encapsulant and the cells	Increased light reflection Water penetration in the structure
Discoloration	UV rays combined with high temperatures and water	Decrease of the generated power
Hot spot	Cell shading	Energy loss transformed into heat
Orientation and tilt	Insufficient surface Panel sagging	False forecast Decrease of the energy capture by the modules
Voltage drop	High current; Low section	Energy loss
Joule effect	Cables heating	Energy Loss transformed into heat
Conversion loss	Inverter efficient	Low power loss
No grid	Electrical parameters not compatible with those of the grid	Open circuit operation of the PV generator

The amount of energy lost is obtained by subtracting the theoretical energy of the plant from the actual energy obtained during an hour of time. The meteorological and electrical parameters are measured and known for the determination of the theoretical energy that should produce the plant. It will remain only to deduct the losses of energy due to the disconnections by instability of the electric network. Thus we distinguish:

- The efficiency of the inverter which is the ratio of the output power of the inverter on its input power.

$$\eta_{ond} = \frac{P_{ac}}{P_{dc}} \quad (1)$$

η_{ond}: Inverter efficiency.

P_{ac} (kW): Alternating power inverter.

P_{dc} (kW): Inverter continuous power.

- Voltage drops which are losses due to the connection cables at the junction box and the electrical tables.

$$\Delta U = \frac{\rho * L * I}{S * U} \quad (2)$$

- The form factor is one of the most important values for evaluating the efficiency of a photovoltaic system.

$$FF = \frac{P_{\max}}{V_{oc} * I_{sc}} \quad (3)$$

$$P_{\max} = V_{opt} * I_{opt} \quad (4)$$

It is equal to 0.8 for plants with normal operation [10].

2.4. Application

In order to determine the coefficients for the various losses accurately, we used the peak data for each month over the three month study period (January, February, and March). The data are measured and recorded in one-minute steps. Table 6 shows the meteorological data corresponding to the monthly peak irradiance.

- The loss coefficient at the inverter is represented by the letter K_1. The conversion efficiency is a measure of the losses incurred during the conversion from DC to AC. These losses are due to several factors: the presence of a transformer, magnetic losses and associated copper losses, and self-consumption of the inverter. Table 7 shows some values collected at the inverter level to calculate its real efficiency.

- Voltage drop coefficient K_2

The voltage drop coefficient K_2 expresses the connection cable losses. The voltage drop must be calculated for each cable of the PV array, each cable of the PV junction boxes, and for the cable of the inverter. The cumulative voltage drop of the cables between each string and the inverter is then calculated. Table 8 shows the current and voltage measurements at the various nodes of the system.

ΔU_a: Voltage drop of the cables connecting the junction box to the inverter.

ΔU_b: Voltage drop of the cables connecting the PV panels to the junction box.

$$K_2 = 100\% - 0.271\% = 99.7\%$$

- The tilt coefficient, this value is related to the angle of inclination, orientation and fixation of PV modules. It is measured using the solar disk in the Dakar region. The CICAD PV solar power plant has a PV module tilt of 6˚C and an orientation of 24˚C south. The tilt coefficient (K_3) is therefore 0.99.

- The form factor coefficient K_4 is the average of the calculated form factor values divided by 100.

Table 6. Hourly data for the monthly daily peak.

Year	Month	Time	Irradiance (W/m^2)	Ambiante Temperature T_a (˚C)	Module temperature T_m (˚C)	Open circuit voltage max V_{ocm} (V)	Short circuit current max I_{scm} (A)
2017	Janu	12 h 53 mn 13	783	34	59.309	36.460	6.894
	Feb	12 h 57 mn 29	937	27	57.286	36.751	8.250
	March	12 h 56 mn 39	906	29	58.284	36.607	7.977

Table 7. Comparisons of the power ratios between the input and the output of the inverter.

P_{AC} (W)	421	520	670
P_{DC} (W)	413	510	657
Efficiency (K_1)	98.1%	98.1%	98.1%

Table 8. Voltage drop calculation.

U_{table} (V)	I_{table} (A)	I_{box} (A)	ΔU_a (V)	ΔU_b (v)	Cables losses
678	47.55	9.51	0.11%	0.16%	0.27%

$$K_4 = \frac{100 - (\text{average of FF})}{100} \tag{5}$$

$$K_4 = (100 - 0.75)/100.\ K_4 = 0.99$$

- Calculation Power injected into the grid (P_{inj})

The electrical power at the output of the inverter is the module power multiplied by the different loss coefficients of the PV system.

$$P_{inj} = P_{field} * K_1 * K_2 * K_3 * K_4 \tag{6}$$

The field power is the power of all the photovoltaic modules in the plant. It is obtained by multiplying the power of a module by the total number of solar panels [11].

$$P_{field} = P_{pv} * N_m \tag{7}$$

P_{field}: PV field power; N_m: number of modules

The module power P_{pv} represents the measured module power. It is obtained from the measured values of the open circuit voltage, the short circuit current and the form factor [10].

$$P_{pv} = V_{co} * I_{cc} * FF \tag{8}$$

3. Results and Discussion

The coefficients of the different losses are calculated, the duration of the disconnections noted as well as the meteorological parameters. We can calculate the amount of energy lost during the whole observation period and their percentage on the global production. **Table 9** shows a daily report of the CICAD solar power plant and **Table 10** shows the results obtained from 02 to 09 January 2017.

Table 9. Daily CICAD report of 02/18/2019 [12].

Headings	Unit	Inv1	Inv2	TOTAL
Grid absence (lost hours)	h			0:44
Production duration	h			7:16
Sunshine duration based on weather	h			8:00
Number start				5
Peak of the day	KW	910	917	1827
Gross production	KWh	4612	4637	9 249

Table 10. Summary from 02 to 09 January 2017.

Date	Disconnection periods	Irra diance (W/m²)	Estimated Power (kW)	Grid absence duration	Lost energy (kWh)	η_{pv} (rendement)	K_1	K_2	K_3	K_4
	9 h 17/9 h 25	215	365.897	0.133	48.786	3.194	0.980	0.970	0.900	0.992
01/02/2017	12 h 10/12 h 24	768	1222.582	0.233	285.269	10.671	0.980	0.970	0.900	0.992
	12 h 46/12 h 53	276	465.970	0.117	54.363	4.067	0.980	0.970	0.900	0.992
01/03/2017	10 h 02/10 h 08	476	786.072	0.100	78.607	6.861	0.980	0,970	0.900	0.992
01/04/2017	16 h 24/16 h 27	369	615.979	0.083	51.332	5.377	0.980	0.970	0.900	0.992
01/05/2017	9 h 38/9 h 44	430	714.914	0.100	71.491	6.236	0.980	0.970	0.900	0.992
01/06/2017	8 h 25/8 h 32	169	289.556	0.117	33.782	2.524	0.980	0.970	0.900	0.993
	14 h 32/14 h 39	753	1203.390	0.117	140.395	10.482	0.980	0.970	0.900	0.994
	9 h 58/10 h 05	522	860.147	0.117	100.351	7.487	0.980	0.970	0.900	0.994
01/07/2017	10 h 22/10 h 28	630	1025.490	0.100	102.549	8.920	0.980	0.970	0.900	0.995
	10 h 38/11 h 15	684.87	1107.906	0.617	683.208	9.631	0.980	0.970	0.900	0.996
01/08/2017	9 h 00/9 h 05	123	212.506	0.083	17.709	1.846	0.980	0.970	0.900	0.997
	15 h 48/15 h 57	613	999.317	0.150	149.898	8.675	0.980	0.970	0.900	0.997
	12 h 01/12 h 16	470.63	781.559	0.250	195.390	6.780	0.980	0.970	0.900	0.998
01/09/2017	15 h 10/15 h 17	334.13	564.211	0.117	65.825	4.891	0.980	0.970	0.900	0.999
	15 h 22/15 h 29	282	479.438	0.117	55.934	4.153	0.980	0.970	0.900	0.999
TOTAL				**2.55**	**2135**					

The special case of **Table 9** shows how the amount of energy produced, the duration of disconnections as well as the daily peak, are recorded in the daily report. This makes it easy to aggregate the total duration of disconnections and the amount of energy produced during the study period.

We note during the period from January 02 to 09, 2017, there were several disconnections due to the instability of the electrical grid, During the period from January 2 to 9, 2017, there were several disconnections due to the instability of the electricity network, with a peak of lost energy of 879 KWh recorded on January 7, 2017. The causes of grid instability are of several types among which we can mention: automatic load shedding due to lack of production, fault tests, grid incident, etc. The total duration of generation interruptions during this period is 2.55 hours and the corresponding lost energy estimated at 2.1 MWh.

Based on the complete summary of the three months studied, we present in **Table 11** the amount of energy lost, the total duration of disconnections as well as the amount of energy produced during our study period.

Table 11. Quarterly summary of network unavailability.

Month	Grid instability duration (hour)	Energy injected (kWh)	Lost Energy (kWh)	Real calculated energy (kWh)	% Ratio E_{lost}/E_{real}
January	22.1	278,167	20,156	298,323	6.75%
February	12.3	291,451	921	292,372	0.31%
March	12.3	334,619	1432	336,051	0.42%
Total	46.7	904,237	22,509	926,746	2.4%

It can be seen that the monthly producible during the first quarter of the year is around 3 Gwh. But the lost energy rates for the months of February and March are almost nil (0.3%) unlike the month of January which recorded a rate of 7%. This difference is explained by the high duration of network instability during the month of January, which corresponds to an inverter disconnection duration equivalent to 22 hours.

4. Conclusions

An evaluation of the amount of energy not produced as a result of grid disconnections is presented in this study. The different technical energy losses are determined and classified into four types: aging of the photovoltaic modules, tilt of the photovoltaic modules, voltage drops and inverter efficiency. The factor of each type of loss is taken into account in the evaluation of the amount of energy produced by the photovoltaic field. The first results obtained after the study of three months of operation of the disconnections of the CICAD power plant, due to the instability of the Senelec distribution grid are:

- The amount of energy lost is estimated at 22.509 kWh.
- The percentage of energy lost is 2.4% of the total calculated energy that the plant was to produce.
- The total duration of the disconnections is equal to 46.7 hours.

However, it is very difficult to quantify the unproduced energy with precision. Finally, it should be noted that it is very rare to find research that gives results on the energy lost due to the instability of the electrical grid.

In the future, studies on longer periods and on larger power plants would be very relevant as well as work on the causes of disconnections.

Conflicts of Interest

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

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