Estimation Of Variations Of Electrical Parameters In Low Voltage Networks Due To Rapid Fluctuations Of Solar Irradiance: A Case Study Of A Photovoltaic System In Bucaramanga, Colombia.

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***Abstract*— The power injection of photovoltaic (PV) systems depends on the varying behavior of solar irradiance on site. Some studies analyze the impact that rapid fluctuations in solar irradiance can cause on the operation of electrical networks, but there is a lack of methodological proposals to apply. This work proposes a procedure to estimate voltage variations, power flows, and power losses in conductors due to such fluctuations of a case study. The characterization of solar irradiance is carried out with data taken in the PV system of a university building. Additionally, some devices of the intelligent measurement system of the studied building allow data collection in the order of minutes. These data allow generating a simulation of power flow through iterative calculations in steady-state for each minute. It allows to carry out a basic analysis of the behavior of the electrical variables to be studied, taking into account the power injection of the PV system and the effects of intermittence due to cloudiness.**

Keywords*— *Electric Power Distribution Systems (EPDS), photovoltaic (PV) systems, smart metering, intermittent cloudiness, power flows, voltage regulation, conductor power losses.

I. INTRODUCTION

The intermittence in solar irradiance due to the cloudiness of the study site can cause negative impacts on the operation of the electrical networks. The sudden passage of clouds partially obstructs the incident solar irradiance on the surface of the photovoltaic (PV) panels and, consequently, affects the power injected into the grid and the connection point voltage [1] - [3].

Different devices integrate PV systems and aim to transform solar energy into usable electrical energy. Intermittent cloudiness obstructs the flow of light and causes variations in injected electrical power and the operating parameters of interconnected systems [4].

Approximately 85% of the PV panel market in the world is represented by crystalline Silicon (Si) cells. Prospects for PV panels indicate that thin-film panels could dominate the markets. This type of PV panel is more vulnerable to intermittence due to cloud cover than Silicon panels [5].

Trindade *et al.* [6] studied several cases of solar irradiance in a given PV system, showing cases of intermittency in cloudiness. Some of these cases caused drops of up to 80% in generated power with durations of up to 8 minutes. They experimentally demonstrated that a cloudy day may cause up to 248 intense variations in injected power.

These interruptions have effects that can be mitigated with the use of devices that provide reactive power, which tends to be controlled by specialized software [6]. An advanced inverter control loop with voltage regulation is also possible. Control of active power delivered to the system can mitigate instantaneous variations in constantly intermittent conditions. This mitigation works directly in the injection of active power and indirectly in the injection of reactive power.

It is possible to use energy storage to correct injection variations employing battery banks since it can completely mitigate abrupt changes in solar irradiance by instantly filling the power deficit [3].

Research works regarding the impact of intermittence of solar irradiance on the operation of PV systems seek solutions from the design and reduce adverse physical effects on PV systems and the effects in the assets in distribution networks [7]. There is no methodological proposal to study these problems.

For this reason, this work proposes a procedure for estimating rapid voltage variations, power flows, and losses in conductors at the common connection point of low-voltage electrical networks with power injection of PV systems, caused by intermittence in irradiance solar from simulations.

The occurrence of an intermittence in solar irradiance reduces the power generated by the On-grid PV system and increases the demand of the grid to meet the specific demand. For the stand-alone case, the load would be supplied by the battery bank or an auxiliary source. Trindade *et al.* [6] show that the correlation between power variations and fluctuations in solar irradiance due to cloud cover is exactly the unity. This means that the passage of a cloud alters the value of solar irradiance perceived by the PV panel, generating an equal variation in the percentage and duration of the power generated. Due to this, it is possible to satisfactorily characterize the change in solar irradiance in a given time from measurements of the power generated for that period and vice versa.

Voltage drops also have a similar characteristic. Their variations tend to be directly proportional to changes in solar irradiance perceived by PV panels, but cannot be estimated so easily. These variations depend on the supplied load and the devices of the solar PV system [6]. The losses in the conductors depend on the response in the operation of the power system about these changes.

The fluctuations of solar irradiance are modeled from the data measured in the existing solar PV system in a university building by this procedure. A simulation with iterative calculations is carried out including this characterization. This calculation response allows obtaining the estimate of the electrical variations that occur under these conditions in a stable electrical system.

II. Methodology

To achieve a characterization of intermittent cloud cover for the tropical climate of the city of Bucaramanga, Colombia, the PV system that works in the Electrical Engineering Building (EEB) of the Universidad Industrial de Santander (UIS) [8] was studied. There is a smart measurement system to determine demand curves and load behaviors, integrated by lighting fixtures, air conditioners, and office equipment.

A. Procedure for estimating variables

The estimates are based on measurements that can be electrical or meteorological depending on the available devices. These measurements represent the daily behavior of solar irradiance. The characterization of the intermittences of cloudiness is carried out for each minute studied, using statistical analyzes [9] of normal distributions. Each user-defined scenario determines the irradiance curve.

A busbar system is used to model the electrical system studied and its subsequent power analysis. The result of this modeling is an admittance matrix and the identification of the bars as load or compensation. The load curves of the electrical system studied are given by the same method of statistical measurements and distributions or by design data and load estimation. The power system, a PV power injection curve, and a demand curve are the input data of the simulation and the result of this modeling.

The simulation is performed with an iterative power flow analysis with the data obtained for each minute of the day. Each result feeds a general table that stores the observed variations.

B. System studied

The PV system is integrated by 37 PV panels for self-generation (9.63 kWp) and 8 smart meters on the upper terrace of the EEB in UIS, located in Bucaramanga (Colombia). Its objective is the study of the impact on the distribution network by the injection of photovoltaic energy [10].

The measurement of the electrical variables was carried out with the ACUVIM IIR smart meter, located at the exit of the PV system of the EEB, with intervals of one (1) minute. A total of 67,882 records were taken from November 2018 to January 2019. The are distributed by date, hour, and minute to perform the characterization of a day on the site of the measurements within the city of Bucaramanga.

According to the Institute of Hydrology, Meteorology and Environmental Studies (*Instituto de Hidrología, Meteorología y Estudios Ambientales* – IDEAM) [11], the city of Bucaramanga has a dry temperate climate, with an average annual total rainfall of 1303 mm. During the measurement days, it is considered the end of the rainy season and the beginning of one of the two dry seasons of the year, where it can rain about ten (10) days a month. During this period there is a slight drop in ambient temperature and an average of five (5) to seven (7) hours of sunshine. In the rainy months, it can fall up to 4 hours of sunshine.

These data establish the bases of the characteristic solar irradiance curve and of the PV injection that is supplied in the simulation. These parameters define the two simulation scenarios to work within this document. The electrical system of the EEB and its load demand is established for the response of the solar PV system to a stable irradiance (clear day) and a highly variable irradiance (cloudy day).

Through data analysis and statistical processes, it can be established that the solar irradiance probability curves for each minute show a normal distribution, separating the data into two groups: clear day and cloudy day. From this conclusion, a characterization of the solar irradiance can be performed for the measurement point. This can be modified according to input data supplied by the user or it can be set randomly.

The measurements of other smart meters are used to obtain the input data of the load and to characterize the minute-by-minute demand curves and thus obtain a stable simulation response.

C. Simulation

The power flow analysis will be carried out to the system shown in Fig. 1. The PV power injection takes place in Bar 2. Bar 1 fulfills the compensation function. Bars 2 to 7 are load bars.

With the load and PV power injection curves, plus the impedance eigenvalues of the EPDS, the iterative process is carried out every minute. Bar 1 is the EPDS transformer, its objective will be to supply the general demand and relieve the PV system when it suffers the effects of solar intermittency.

III. Results

For this analysis, the comparison is made between the indirect irradiance curve obtained randomly in this document, together with a curve that only takes values of 50% of normal probability, with clear day distribution data, simulating an average and clear day in its totality, as shown in Fig. 2.

A. Voltage results

When using the transformer bar (Bar 1) as compensation, a “stable” value of 220 V remains as a reference for the other bars. This voltage depends on the external medium voltage electric power distribution system, so any abrupt variation in external power flows can affect this value.

The PV system is integrated into Bus 2. The increase in voltage can be observed at the moments when the power injection into the system occurs. It is observed in Fig. 3 that there is an increase in voltage of approximately 2.5% when energy is being generated. Similarly, there is a 2.5% drop when a load of Bar 8 (fourth floor) is high at night and there is no generation.

An expected result is obtained where one of the conclusions of Trindade *et al*. [6] concerning the voltage, since it tracks proportional to the irradiance curve, depending on the load that feeds.

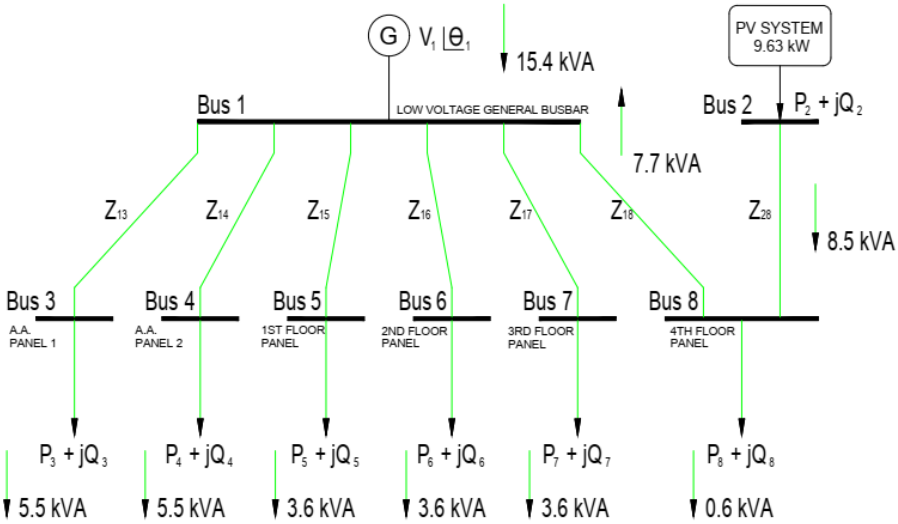

Fig. 1. Busbars diagram representing the studied EPDS and ower flows in the electrical system for 11:01 a.m. Source: Authors.

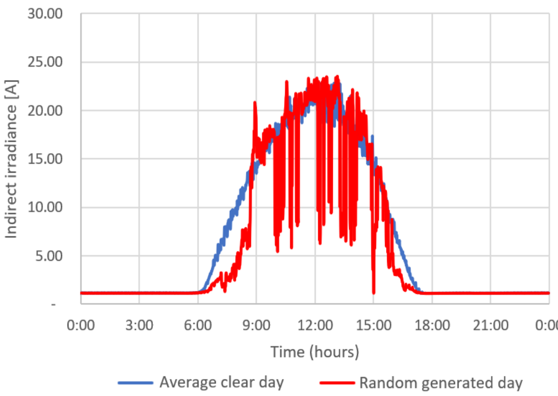

Fig. 2. Solar irradiance for each simulation. Source: Authors .

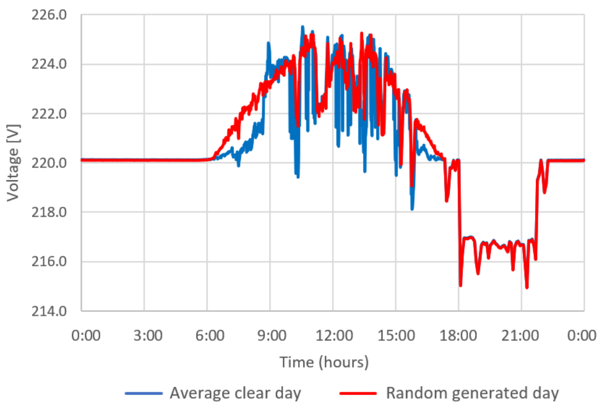

Fig. 3. Voltage in Bus 2 for the generated day. Source: Authors.

The load bars have a similar behavior due to the way they were proposed, there is only a change in the magnitudes. It is observed that the greatest voltage drop was in Bar 4 with 0.64%. In none of these bars was a representative voltage variation, because the injection of energy from the PV system is mostly consumed in Bar 8. The energy not consumed in this bar is transmitted to the compensation bar and to the other bars connected. The variations that may exist in the tension of these bars for a clear day and a cloudy day are minimal and depend on the physical parameters of the system.

It should be clarified that solar irradiance can affect the demand for electrical energy in a specific situation. Variations in solar irradiance have effects on the use of electrical devices such as air conditioners and lighting. For example, when there is a considerable drop in solar irradiance, the PV generation decreases and the electrical load increases due to the use of artificial lighting. In this case, there is a considerable variation in the voltage of the bars of the system. This is a direct analysis of the variations in the PV generation of the electrical system due to the effect of intermittent solar irradiance, without focusing on the changes that may occur in the load due to this phenomenon.

B. Conductor power losses results

Power losses in conductors occur as a consequence of the *Joule effect*. The energy that is transmitted by a conductor in the form of electric current is transformed into heat, increasing its temperature [12]. This phenomenon occurs as a response to the movement of electric charges in the resistive part of all the impedances shown in Fig. 1. Therefore, its magnitude depends on the conductor's resistivity, the connection distance, and the power flow between bars.

The transformer used as a feeder in this simulation has an internal impedance and losses due to the *Joule effect*; However, as it is not the object of study in this application work, its internal characteristics are not available and they were considered negligible.

The power losses in the lines that join Bar 1, with Bars 3 to 7, where the load curve was estimated by measurements, the response in losses is very similar. Fig. 4 shows these variations.

It is not considered that there will be a different effect with the inclusion of the PV system since its scope for this line is almost nil. Also, the current flow always comes from Bar 1, regardless of the PV injection. These losses have a maximum percentage value of 0.51%. This case complies with Colombian regulations [13].

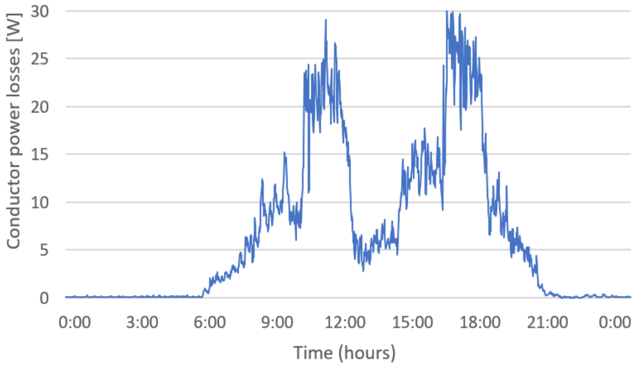

Fig. 4. Power losses between Busbars 1 and 3. Source: Authors

It should be noted that the calculation of percentage power losses is different for power flow. In this case, the losses for the transmission between the feeder Bar 1 and its load on Bar 3 are being taken into account. Losses are different if they are calculated from the feeder on Bar 2 (PV System) up to the load point.

For power losses in the line that joins Bar 1 with Bar 8, it must be taken into account that on the day the power supply of this bar comes from Bar 2 with the injection of the PV system and from Bar 1 in the solar irradiance drops. Fig. 5 shows the behavior of losses on this line.

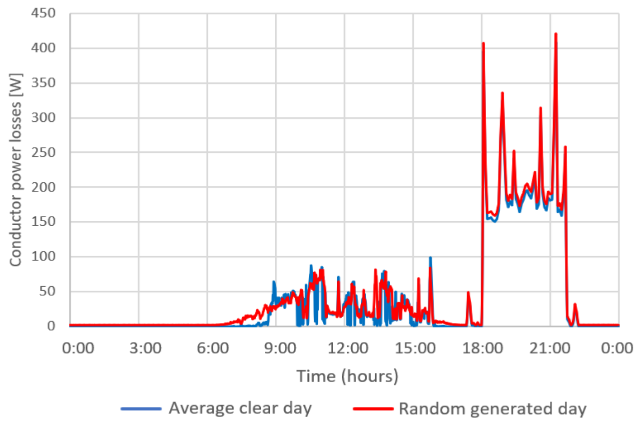

Fig. 5. Power losses between Busbars 1 and 8. Source: Authors.

It can be seen that when there is power injection by the PV system, the losses in the line that feeds Bus 8 from the transformer are reduced. Solar irradiance fluctuations generate greater power flow from Bar 1.

The power losses in the line that joins Bar 2 with Bar 8, are presented as a quadratic function with the current generated by the PV system and with the solar irradiance due to their direct relationship. The losses are seen as a representation of the solar irradiance curve for both cases. It should be taken into account that the reduction of power losses in lines 1-8 due to the increase in power injection by the PV system is seen in lines 2-8, so an optimization analysis of power losses may be required.

C. Power losses and flows relation

A maximum value of 131 W of losses in the conductors is observed, which occurs when the PV system has a maximum injection of approximately 9 kW. As a percentage, it means 1.45% power losses and complies with the Colombian standard in terms of its design. This calculation is given when the energy generated by the PV system is consumed in Bar 8 and it does not consider that this source can feed the other bars.

For example, at 11:01 am, you have an injection of power from the PV system of 8.47 kW while the consumption of bar 8 is 0.6 kW. Likewise, the power losses in the conductors that connect Busbars 2 and 8 are 112 W. It can be concluded that the excess power is transmitted up to Bus 1 by the conductors that connect it with Bus 8 and from there, up to the other bars, producing additional losses. This means that the losses seen in Z_{28}, the losses in Z_{18}, and the losses in the other lines must be added concerning the proportion of electrical energy transmitted from the injection in Bar 8.

Fig. 1 shows in detail the power flow for 11:01 a.m. of the simulation made. It is assumed that the losses in the bars are negligible for the performance of the exercise.

The load from busbars 3 to 7 is supplied by the transformer and the PV system simultaneously. There is a path for the flow of energy between Bar 2 and Bars 3 to 7, whose losses must be considered since they can be high.

D. Transmission and power flow results

The power transmission between bars is obtained from the transmission current and the voltage of each bar. Power transmission can be viewed as apparent power with its angle. In this case, real power and reactive power are displayed to better visualize the flow between bars.

The power flow in the lines that join Bar 1, with Bars 3, 4, 5, 6, and 7 are not affected by the variations in the photovoltaic injection.

In the power flow in the line that joins Bar 1, with Bar 8, it is possible to fully identify the change in the direction of the power flow when the PV generation exceeds the load demanded in Bar 8. Fig. 6 shows active power flow. When positive it indicates a flow from Bar 1 to Bar 8 and vice versa. Reactive power has a minimal effect on the PV system since the system works with a capacitive power factor very close to unity. The reactive power curve, shown in Fig. 7, does not show much difference from the power demand curve of Bar 8.

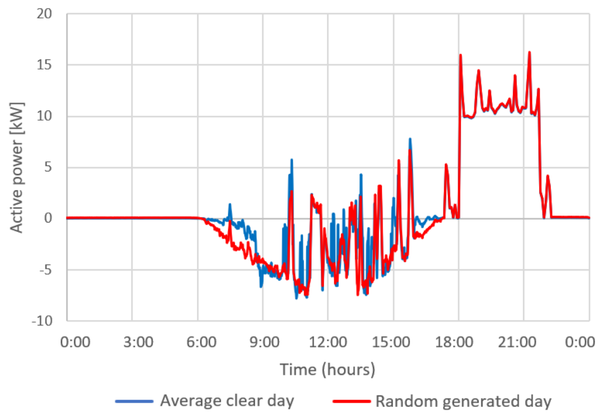

Fig. 6. Active power flow between Busbars 1 and 8. Source: Authors

Problems that may arise in an existing PV system or designing a new one can be caused by this "reverse" power flow, because there may be some changes in the system bus voltage and differences in power losses concerning the same system without PV injection.

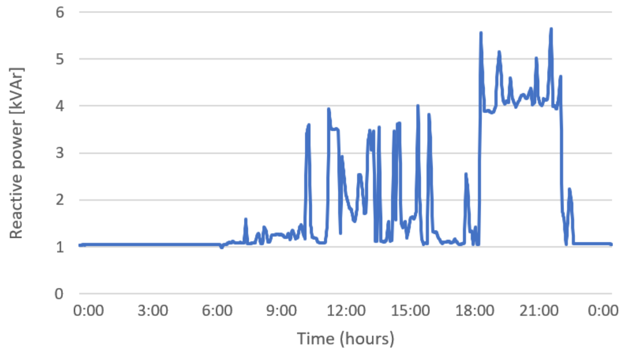

Fig. 7. Reactive power flow between Busbars 1 and 8. Source: Authors

In this case, the abrupt changes in cloud cover simulated can be observed, in addition to the variations in the demand of the bus, that can cause sudden changes in the system, which could affect the integrity of the same or produce additional losses. The power flow in the line that joins Bar 2, with Bar 8 is the connection line of the PV system with the load, the power flow that is observed is that generated by the PV injection in terms of active power. For the reactive power sizing in the simulation, a constant value of 10% of the maximum value of the active power delivered to the system was used.

E. *Summary*

Table 1 summarizes the findings of the variations found by the PV injection with intermittent irradiance.

TABLE 1. SUMMARY FINDINGS.

	Variations		
	Voltage	Power flows	Conductor power losses
Bus 1 (Compensation bus)	Compensation and reference bus	The connection with Bar 8 shows a variation of direction according to the PV generation and consumption in the bus.	Losses vary in the connection with Bus 8 since they decrease when Bus 2 feeds Bus 8. However, the losses generated by having reverse flow must be taken into account.
Bus 2 (PV generation bus)	The voltage in this Bus has a direct correlation with the irradiance curve.	Power flow depends exclusively on irradiance and PV generation.	Losses with Bus 8 depend exclusively on the flow of power generated.
Bus 3 to 7 (Load busbars)	The voltage curve depends on the load, the PV generation has little or no effect.	It only has a connection from Bus 1; therefore, the flows depend on the load and not on the PV injection.	The losses depend on the load and the flow from Bar 1, they do not distinguish if the energy used comes from the PV generation or the Compensation Bus.
Bus 8 (Special load bus)	The voltage curve depends on the PV generation and its ability to cover the load of the Bus.	The power flow changes direction depending on which bus the power comes from.	Losses depend on the source of the energy flow.

IV. Conclusions

The characterization of intermittent cloudiness carried out in this work can be scaled to any climate because it is a probabilistic analysis of measurements made.

Any project derived from the characterization carried out in this work must be sustained in warm tropical contexts, since the base conclusion of this study, concerning the normal distribution of the probabilities of irradiance per minute, was only studied for this type of weather. It can also be scaled to different work scenarios, such as completely cloudy or clear days, specific schedules, and probabilities.

In the simulated power flows can be observed that in the bars where there is a direct PV injection and to a lesser extent in the adjacent bars, there will be variations that may affect the integrity of existing systems that are not designed for PV injection.

It can be understood that the variations by solar intermittency are in the temporal order of seconds and the electrical transients in the order of milliseconds; however, it is recommended to review the study of these rapid variations and the possible transient effects in electrical machines.

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