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Optimal power flow model for building integrated photovoltaic systems operating in the andean range

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ABSTRACT

This paper presents a novel model to evaluate the power output of a building integrated photovoltaic system (BIPVS) operating in the Andean Range. The Optimal Power Flow (OPF) model optimizes the power output of the BIPVS within an electrical system without violating operational limits. The model is validated with the experimental performance of a 6 kW BIPVS installed in Bogota, Colombia. The meteorological data affect the power flow. The model is evaluated under sunny and rainy days to characterize the photovoltaic array performance. The results showed that the AC PV-energy generation was 5,904 kWh/year for 2017 and that there is a correlation factor of 99.87% between the experimental power flow and the proposed model.

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1. INTRODUCTION

Building Integrated Photovoltaic Systems technology allows the use of the façade or the roof of buildings of any type to produce electricity (or thermal heat in the case of solar collectors) and in this way the building reduces its energy demand. These technologies integrated into buildings allow developing various designs of structures in broad ways [1]. The photovoltaic generator (PV), the main component of PV technology, is responsible for the efficiency and durability of the entire system. This generator is used by many designers to replace parts of the structure of buildings such as ceilings or walls. The meteorological variables directly affect the performance of an interconnected photovoltaic system generating losses and affecting the economic balance of the System [2].

There are worldwide different standards that establish the requirements for the connection of photovoltaic systems interconnected with the electricity grid. These standards aim to ensure the safety of people and equipment. Conventional generation of electricity has been through hydropower and renewable energy generators are being used recently to produce electricity [3].

One of the advantages of the building integrated photovoltaic systems, is that they can reduce the space and the cost of certain equipment if they are used to be installed in structures [4-6]. In the case of thermal energy, changes in temperature and energy transfer to the interior of the building, makes the process not easy, [7- 10], which directly affects the entire structure where the System is installed [11].

Traditionally, power distributions grids deliver power in a single direction, to supply the electricity required by users. Energy companies are responsible for purchasing power in the electricity market and selling it to the end user at defined prices [12].

The analysis of the optimal power flow (OPF) represents a valuable technical-economic technique. With this type of analysis it is possible to optimize a specific variable of the Power System in order to guarantee the reliability and the proper operation of the energy processes [13].

There are in literature several papers showing methods to evaluate the operational results of photovoltaic generators and the impact of meteorological data [14–21] and to develop different non-linear electric models used to describe the characteristics of the PV modules under non-standard conditions [22-29]. This paper presents a method to model the optimal power flow of BIPV systems. Section 2 addresses the BIPVS model dynamics. Section 3 presents the designing process of the OPF model. In Section 4, to approve the developed model, monitored data from one photovoltaic generator in Bogota, Colombia is utilized to make comparison with the proposed OPF method. Conclusions with discussions are given in Section 5.

2. BUILDING INTEGRATED PHOTOVOLTAIC SYSTEM MODELLING

The BIPV system performance is influenced by solar irradiance and ambient temperature. These variables are dependent of the specific installation site and must be analysed for a period of one year. The electric components of the BIPV system are modelled as follows.

2.1. Photovoltaic Current

Each solar cell behaves in the dark in a similar manner to a p/n rectifying diode, and generates an electrical photocurrent under the incidence of light. The photovoltaic current is given by:

$$Iph = \frac{G}{1000}[Isc + \Delta i(T - Tr)] \tag{1}$$

G is the radiation in the existing site, T and Tr are the site's current temperature and the reference temperature, Δi is the current temperature coefficient and Isc is the short-circuit current of the cell at standard temperature. The solar cells integrating the solar module are described by:

$$I = I_{ph} - I_s * \left(e^{\left(\frac{V+R_S*I}{n*V_t}\right)} - 1\right) - \frac{V+R_S*I}{R_{sh}} \tag{2}$$

Where, Is is the saturation current of the diode, V is the saturation voltage, Rs is the series resistor of the module and Rsh is shunt resistor module.

2.2. Inverter Model

The PV inverter is modelled as a voltage element that supplies the current described by this equation:

$$I_{RMS} = \frac{V_{mpp}*I_{mpp}*nf}{Vred_{RMS}} \tag{3}$$

Where Vmpp is the maximum power point at the inverter input and nf is the efficiency.

2.3. Electrical Grid Model

This proposed model is an RLC circuit with a power factor equal to 0.85. The following expression gives the angle for that variable:

$$\theta = \arccos(0.85) = 31.7° \approx 30° \tag{4}$$

Taking expression (5) into account, values are calculated with R = 3Ω, X =$\sqrt{\mathbf{3}}$. Inductive (XL) and capacitive (XC) reactance are evaluated using (6) and (7).

$$Tan\theta = \frac{(X_L - X_C)}{R} = \frac{\sqrt{3}}{3} \tag{5}$$

$$X_c = \frac{1}{2*\pi*f*C} \tag{6}$$

$$X_L = 2\pi f L \tag{7}$$

With L = 2H and equation (8), we can calculate the capacitance (C):

$$C = \frac{1}{\omega^2 L - \omega\sqrt{3}} = 3.526 * 10^{-6} F \quad (8)$$

3. OPTIMAL POWER FLOW MODEL

The OPF problem is as [13]:

$$\min f(z); s.t.: \begin{cases} I_{Re}(z) = 0, \quad I_{Im}(z) = 0 & (9.1) \\ g(z) = 0, \quad h(z) = 0 & (9.2) \\ \underline{z} \le z \le \bar{z} & (9.3) \end{cases} \quad (9)$$

f(z) represents the objective function; I is the total current applied to all points; g(z) and h(z) are the inequality constraints, respectively; and z denotes the state and control variables.

The Lagrange function is the following:

$$L(z,\lambda,\pi) = f(z) - \sum_{i=1}^{N} \lambda_{Im,i} I_{Re,i}(z) - \sum_{i=1}^{N} \lambda_{Re,i} I_{Im,i}(z) - \sum_{i=1}^{ni} \lambda_i \, g_i(z) - \sum_{j=1}^{nd} \pi_{j.1}(z_j - z_{j.min}\, sl_{j.1}) - \mu b \sum_{j=1}^{nd} \log(sl_{j.1)} - \sum_{j=1}^{nd} \pi_{j.2}(z_j - z_{j.max} - sl_{j.2}) - \mu b \sum_{j=1}^{nd} \log(sl_{j.2}) \quad (10)$$

In this equation, ni is the total of restrictions, nd is the total of inequality restrictions; $\boldsymbol{\lambda_{Re}, \lambda_{Im}, \pi_1}$ ***and*** $\boldsymbol{\pi_2}$ represent the Lagrange factors; sl= group of variation range; and $\boldsymbol{\mu b} > \mathbf{0}$ is the barrier variable [13]. Then, our method is described by:

$$\nabla^2 L(z,\lambda).\Delta(z,\lambda) = -\nabla L(z,\lambda) \quad (11)$$

$\boldsymbol{\nabla^2 L(z,\lambda)}$ represent the Hessian matrix and $\boldsymbol{\nabla L(z,\lambda)}$ is the first-order derivatives.

Finally, our system is described by:

$$\min_{\substack{E_1 \\ E_M(t+dt)}} \left\{ \begin{array}{c} \Delta V \begin{pmatrix} E_1,\ E_1(t+dt),\ E_2, E_2(t+dt), \\ \dots, E_M, E_M(t+dt) \end{pmatrix} \\ + V(t+dt, E_1(t+dt), E_2(t+dt), \\ \dots, E_M(t+dt)) \end{array} \right\} \quad (12)$$

where V(.) is defined as [30].

4. VALIDATION RESULTS AND DISCUSSION

4.1. System Description

The energy output of the proposed model is verified with measured data from a 6 kW BIPV system. The BIPV system is installed in Bogotá, at 4°35' latitude and 2.580m altitude, on the roof of the "Researching Center of the Engineering Programs – CIPI" building at Universidad de Bogotá Jorge Tadeo Lozano. The BIPV system is composed of 24 photovoltaic modules connected to the electrical grid through a 5000W SMA inverter. A monitoring system was implemented using virtual instrumentation to measure irradiance, ambient temperature and DC-AC variables of the photovoltaic system [9].

Table 1 shows the data sheet of the PV modules used as photovoltaic generator. Table 2 shows the characteristics of the SB 5000TL-US inverter. Figure 1 is an exterior view of a part of the PV array seen from the southeast side of building's roof.

Figure 1. External view of the BIPV system in the laboratory building

4.2. BIPVS Performance

The BIPVS energy production was evaluated for every month of 2017. Figure 2 shows the variation of the photovoltaic array's energy and the AC inverter´s energy.

Due to the location of Bogotá on the Andean range, the presence of clouds is permanent and energy production varies along the whole year. The DC output energy averages 676.2 kWh-day for 2017, with a minimum of 548.3 kWh-day in September and a maximum of 780,6 kWh-day in January. The DC energy includes the conversion losses from solar irradiance to electricity by the solar panels.

The AC output energy averages 585.4 kWh-day for 2017, with a minimum of 482.2 kWh-day in September and a maximum of 679,8 kWh-day in February. The AC energy includes the conversion losses from DC power to AC power by the solar inverter.

Figure 3 shows the efficiencies variation: inverter, PV array and BIPVS efficiencies. The inverter performance was according to the manufacturer's data sheet: its efficiency varied between 90% and 96%.

The PV array efficiency averaged 13.2 % for the year of monitoring, with a minimum of 11.3 % in September and a maximum of 14.2 % in November. BIPVS efficiency is the lowest of those presented, because its calculus includes the PV array and the DC/AC inverter losses. Its average was 10.4%/year with a variation between 9.8% and 11.2%.

Table 1. Electrical Specifications of the PV Module

Electrical data in STC conditions	Value
Rated Power-Pmax (Wp)	250
Rated power tolerance (%)	0/+3
Voltage at the point Pmax-Vmpp (V)	29.8
Current at the Pmax-Impp point (A)	8.38
Open Circuit Voltage-Voc (V)	38.1
Short circuit current-Isc (A)	8.91
Module Efficiency ηm %	15.3
Number of cells in series	60
Nominal Operating Temperature (°C)	44
Kv. Temperature coefficient Voc (%/K)	-0.32
Ki. Temperature coefficient Isc (%/K)	0.053

Table 2. Technical Data of the Selected Inverter

Technical data	Value
DC Maximum input power (W)	5300
DC Rated Voltage (Vdc)	310
Minimum DC Voltage (Vdc)	250
Inverter starter voltage (Vdc)	300
Operating voltage (Vac)	208
AC Rated power (W)	5000
Frequency of the grid (Hz)	60
Maximum output current (Aac)	24
Efficiency (%)	96.7

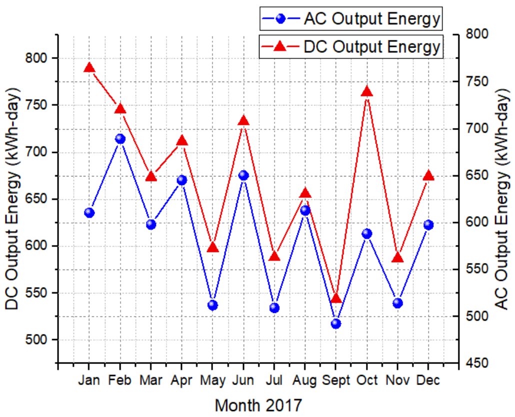

Figure 2. Yearly profile of the DC and AC Energy in Bogotá for 2017

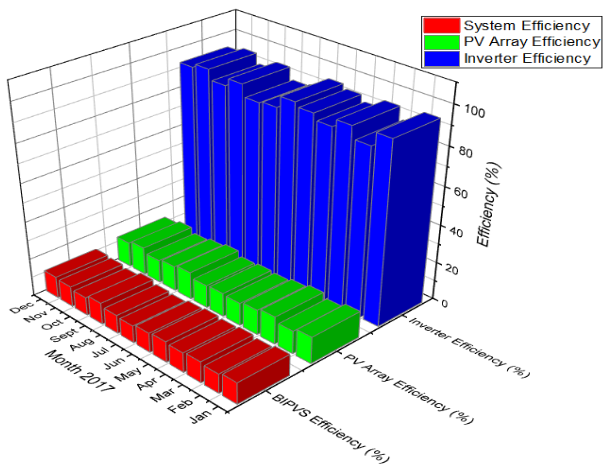

Figure 3. Efficiency data of the different components of the photovoltaic system for 2017: inverter, solar panels, complete system (includes from the inlet of the solar panels to the inverter output)

4.3. OPF Model Results

The daily monitoring is activated between 6 am and 6 pm, acquiring 1 sample per minute of meteorological and electrical variables. The DC and AC output power of the model is obtained by dividing energy in kWh by 12 h (daily monitoring period).

The results are verified considering two kinds of weather conditions: sunny and cloudy. Figures 4 and 5 show the comparison between measured (blue line) and simulated, with the OPF model, (red line) power output for a sunny day (18th January 2017) and a cloudy day (9th October 2017).

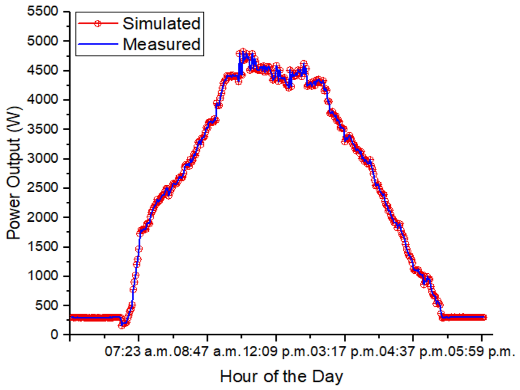

Figure 4. Comparison between the measured and simulated power output for a sunny day

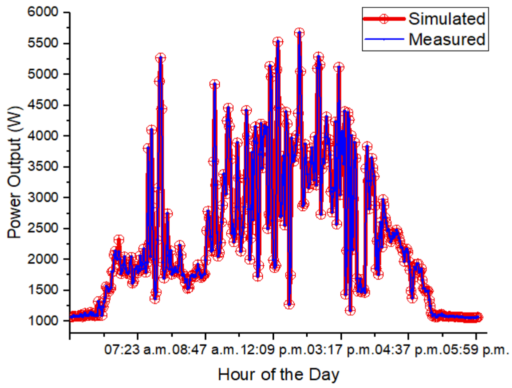

Figure 5. Comparison between the measured and simulated power output for a cloudy day

The OPF model results followed the measured power output quite well. In Figure 4 the maximum power output was 4834 W produced at noon and the OPF model registered 4833.8 W for the same point. In Figure 5 is possible to see the effect of the Andean range: clouds passing over the PV array along the day. Because of this, the BIPV system efficiency is affected by the reduced solar irradiance over the solar panels.

Figures 6 and 7 show the correlation between measured (blue line) and simulated, OPF model, (red line) power output for the same sunny and cloudy days. Both figures plot the power output versus the measured solar irradiance.

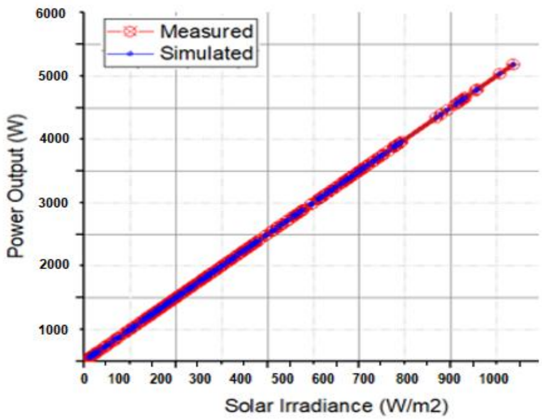

Figure 6. Correlation between the measured and the simulated output power for a sunny day

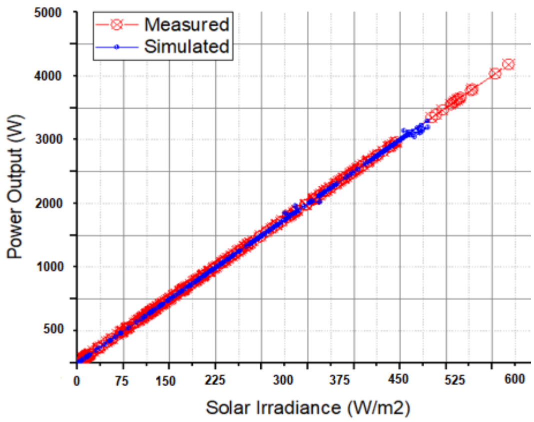

Figure 7. Correlation between the measured and the simulated output power for a cloudy day

In Figure 6 the maximum power output is reached at the standard solar irradiance of 1000 W/m2 presented at noon and it's according to the results presented in Figure 4. This happens because the current photogenerated by the solar panels is directly proportional to the incident solar radiation, allowing to reach the maximum power generation of the System. Thanks to the absence of clouds, there is no dispersion in the data.

In Figure 7, due to the cloudiness condition, the maximum recorded solar radiation was 600 W/m2 and the maximum power generated for this case was 4000 W. This condition also causes small dispersion on data observed. Table 3 shows the correlation results of the experimental analysis.

Table 3. Correlation Results for Both Days

R^2	BIPV System
Sunny	99.87 %
Cloudy	99.62 %

5. CONCLUSIONS

The performance of the BIPV system fulfills the initial design that was expected to produce an average of 504 kWh-day, and the average measured was 585.4 kWh-day. The additional energy (85 kWh-day) was possible due to the good solar irradiance conditions during 2017.

Results about the BIPV system efficiency are also presented. These showed an average of 13.2 % for the photovoltaic array while the AC/DC inverter registered an average of 94.2 %.

This paper presented an OPF model for BIPV systems operating in the Andean range. The model results are validated under different weather conditions. The correlation coefficient for a sunny day registered a value of 99.87% and 99.62% for a cloudy day.

Changes in the national energy regulations as well as support for funding renewable energy generation systems could be incentives for people to install residential photovoltaic systems massively in Colombia.

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