Integration of Photovoltaic Generation in a Microgrid: Spinning Reserve Analysis

Luis E. Luna, *Member IEEE*, Horacio Torres, *Senior Member IEEE*, Andrés Pavas, *Senior Member IEEE*
Department of Electrical and Electronic Engineering
Universidad Nacional de Colombia
Bogotá, Colombia

***Abstract*—This paper proposes a methodology to model and analyze the security scheme required by a microgrid that considers the participation of intermittent energy sources, such as photovoltaic generators (PVG). This security scheme is represented by an up and down spinning reserve.**

The methodology consists of performing a four stages analysis, at each study hour of the next day: a load analysis, which evaluates the uncertainty in the forecast electricity demand; a generation analysis, that evaluates the uncertainty in the forecast power availability of the PVGs; a security analysis, which quantifies and evaluates the up and down spinning reserve required by the microgrid. This reserve allows to drive the system frequency to a steady state after the occurrence of events associated with forecast errors in both the electricity demand and the power availability of the PVGs; and a validation analysis, that verifies the proper sizing of the up and down spinning reserve.

The proposed methodology was implemented on a real microgrid located at the Universidad Nacional de Colombia's campus. From this, it was concluded that the security scheme designed for the microgrid allowed to ensure efficiently the relation between generation and demand, at each study hour.

***Index Terms*—Photovoltaic generation, microgrids, security scheme, spinning reserve.**

I. INTRODUCTION

In recent years, the electricity sector has experienced significant changes due to the introduction of a business oriented market structure. Such structure pretends to achieve higher efficiencies in the electricity supply, i.e. prices that reflect efficient costs and ensure the fulfillment of the quality, reliability and security criteria.

The advances achieved in the electricity sector, along with the high levels of demand growth and the concerns over the management of non-sustainable energy resources have led to the implementation of new generation technology alternatives. These new technologies consider a rational and efficient use of the energy, in such a manner that they have a minimal impact on the environment and contribute to ensure energy availability for future generations. In addition, the development of these technologies (usually of small scale) becomes important again the installation of power plants near to the consumption centers, this time with the power system backup. This is an alternative of high penetration in the electricity sector and is commonly known as Distributed Generation (DG) [1].

The integration of DG within electrical systems and the incentive to optimize energy resources has gained strength in the last years. Accordingly, some countries have adjusted their regulatory policies in order to encourage the DG participation in the electrical systems [2].

Certainly, these regulatory policies have allowed to increase the DG participation in the electricity basket. The increase of the DG penetration, the presence of multiple nearby sources, the implementation of demand response programs and the continued evolution of distribution networks into smart grids have led to the concept of microgrids [3]. A microgrid is an active distribution network that considers the coordinated operation and control of DG sources together with storage devices and controllable loads [4].

According to IEEE 1547-4 [5], microgrids have to satisfy the security requirements that allow these grids to operate in a secure way to any unexpected power requirement. In most cases, this security scheme is represented by a spinning reserve. This reserve represents one of the most important economic dispatch constraints in a microgrid, because it allows to drive the system frequency to a steady state after the occurrence of an event [6] [7].

Microgrids consider the participation of renewable energy sources, such as photovoltaic generators (PVG). The power output of PVGs behaves intermittent due to the variable nature of their primary resources (solar radiation and temperature), and they may even cause security problems in the microgrid. Therefore, it is necessary to design a security scheme for the microgrid, which can respond not only to the statistical forecast errors in the electricity demand (as traditional schemes do), but also to the statistical forecast errors in the power availability of the renewable energy sources [8].

The usual practice is to minimize these statistical errors by means of appropriate forecasting techniques in order to reduce the implementation costs of a microgrid security scheme.

There are different forecasting techniques to analyze time series. The technique based on structural models is one of the most interesting tools to forecast the hourly behavior of the electricity demand, solar radiation and temperature. This technique represents in a very proper way these time series of high density or frequency, seasonal and highly stochastic [9].

L. Luna is a Ph.D. candidate in Electrical Engineer and he is with the Research Program of Acquisition and Analysis of Electromagnetic Signals of the Universidad Nacional de Colombia (PAAS-UN Group). He can be reached at lelunar@unal.edu.co.

H. Torres is a special professor at Universidad Nacional de Colombia and he is the head of the PAAS-UN Group. He can be reached at htorress@unal.edu.co.

A. Pavas is a professor at Universidad Nacional de Colombia and he is with the PAAS-UN Group. He can be reached at fapavasm@unal.edu.co.

This paper proposes a novel security scheme that considers the intermittency of PVGs. In section II, it is proposed a methodology to quantify and analyze the up and down spinning reserve level required by a microgrid to satisfy the security requirements demanded by this type of grids. In section III, it is described the microgrid in which the proposed methodology is applied. In section IV, it is presented the methodology implementation in the microgrid and it is also discussed the results of this implementation. Finally, the conclusions are shown in section V.

II. PROPOSED METHODOLOGY

The proposed methodology allows to model the security scheme required by a microgrid that considers the participation of intermittent energy sources, such as PVGs. The security scheme is represented by an up and down spinning reserve located in the generators of the microgrid with controllable power output.

The methodology consists of performing a four stages analysis at each study hour of the next day: a load analysis, which evaluates the uncertainty in the forecast electricity demand; a generation analysis, that evaluates the uncertainty in the forecast power availability of the PVGs; a security analysis, which quantifies and evaluates the up and down spinning reserve required by the microgrid. This reserve ensures the relation between generation and demand after the occurrence of events associated with forecast errors in both the electricity demand and the power availability of the PVGs; and a validation analysis, that verifies the proper sizing of the up and down spinning reserve.

The demand and the power availability of the PVGs are forecast using the statistical software OxMetrics 6.3 - module STAMP (Structural Time Series Analyser, Modeller and Predictor) and the time series technique based on structural models.

The methodology is implemented by the next steps:

A. Load analysis

1) Acquire and manage the hourly historical information of the electricity demand in the microgrid.
2) Forecast the behavior of the demand, at each study hour of the next day.
3) Identify the up and down standard deviation (statistical error) in the forecast demand, at each study hour of the next day.

B. Generation analysis

4) Acquire and manage the hourly historical information of the solar radiation and temperature in the area where the PVG is located.
5) Forecast the behavior of both the solar radiation and temperature, at each study hour of the next day.
6) Identify the up and down standard deviation in both the forecast solar radiation and the forecast temperature, at each study hour of the next day.
7) Develop the mathematical model of a PVG, which should considers the inverter efficiency and the losses due to the PV module connections. This model has as input variables the solar radiation and temperature, and it has as output variable the AC power availability.
8) Acquire the technical parameters of the PVG interconnected to the microgrid.
9) Forecast the behavior of the power availability of the PVG, at each study hour of the next day. For this, it is required to enter the forecast values of both the solar radiation and temperature to the mathematical model of the PVG interconnected to the microgrid.
10) Calculate the up and down standard deviation in the forecast power availability of the PVG, at each study hour of the next day. For this, it is required to enter the values of the up and down standard deviation bounds in both the forecast solar radiation and the forecast temperature to the mathematical model of the PVG interconnected to the microgrid.
11) If there is another PVG interconnected to the microgrid, it is necessary to go back to item 4. If there is not another PVG, it is necessary to continue with item 12.

C. Security analysis

12) Determine the up and down spinning reserve required by the microgrid, at each study hour of the next day. This reserve allows to counter the uncertainty in both the electricity demand and the power availability of the PVGs.

    The following equations present the mathematical procedure to calculate the up and down spinning reserve.

$$\sqrt{(USDD_j)^2+(DSDP_j)^2}=USR_j \qquad \text{j=1,2,...,24} \tag{1}$$

$$\sqrt{(DSDD_j)^2+(USDP_j)^2}=DSR_j \qquad \text{j=1,2,...,24} \tag{2}$$

Where,

n: Total number of PVGs interconnected to the microgrid.

$USDD_j$: Up standard deviation [W] in the forecast electricity demand, at the jth hour of the next day.

$DSDD_j$: Down standard deviation [W] in the forecast electricity demand, at the jth hour of the next day.

$USDP_j$: Up standard deviation [W] in the forecast power availability of the PVGs, at the jth hour of the next day.

$DSDP_j$: Down standard deviation [W] in the forecast power availability of the PVGs, at the jth hour of the next day.

USR_j: Up spinning reserve [W], at the jth hour of the next day.

DSR_j: Down spinning reserve [W], at the jth hour of the next day.

D. Validation analysis

13) Verify the proper sizing of the up and down spinning reserve, at each study hour of the next day.

The following equations present the mathematical procedure to validate the up and down spinning reserve.

$$RD_j - FD_j = ED_j \quad \text{j=1,2,...,24} \tag{3}$$

$$\sum_{i=1}^{n}(FP_{ij} - RP_{ij}) = EP_j \quad \text{j=1,2,...,24} \tag{4}$$

$$ED_j + EP_j = E_j \quad \text{j=1,2,...,24} \tag{5}$$

$$\begin{array}{lll} \text{if} & E_j > 0 & \text{j=1,2,...,24} \\ E_j & \text{should be} \leq USR_j & \text{j=1,2,...,24} \end{array} \tag{6}$$

$$\begin{array}{lll} \text{if} & E_j < 0 & \text{j=1,2,...,24} \\ |E_j| & \text{should be} \leq DSR_j & \text{j=1,2,...,24} \end{array} \tag{7}$$

Where,

FD_j:	Forecast electricity demand [W], at the jth hour of the next day.
FP_{ij}:	Forecast power availability [W] of the ith PVG, at the jth hour of the next day.
RD_j:	Real electricity demand [W], at the jth hour of the next day.
RP_{ij}:	Real power availability [W] of the ith PVG, at the jth hour of the next day.
ED_j:	Forecast error in the electricity demand [W], at the jth hour of the next day.
EP_j:	Forecast error in the power availability of the PVGs [W], at the jth hour of the next day.
E_j:	Total forecast error [W], at the jth hour of the next day.

E. Methodology Considerations

- The standard deviation in the forecast power availability of the PVG always is asymmetric, because the efficiency of the PVG inverter varies exponentially with the DC power input.
- The up spinning reserve allows to drive the system frequency to a steady state after the occurrence of events associated with: excess in the real demand with respect to the forecast demand, and deficit in the real power availability of the PVGs with respect to the forecast power availability.
- The down spinning reserve allows to drive the system frequency to a steady state after the occurrence of events associated with: deficit in the real demand with respect to the forecast demand, and excess in the real power availability of the PVGs with respect to the forecast power availability.
- The electricity demand is directly proportional to the use of spinning reserve, i.e. an increase in the real demand with respect to the forecast demand implies that the generators with spinning reserve capacity should increase their generation (up spinning reserve application).
- The PVGs are represented as negative loads. Therefore, the power availability of the PVGs is inversely proportional to the use of spinning reserve, i.e. an increase in the real power availability of a PVG with respect to the forecast power availability implies that the generators with spinning reserve capacity should decrease their generation (down spinning reserve application).
- The total forecast error follows a normal distribution with expectation zero and standard deviation described by the up spinning reserve and down spinning reserve. The 68% of the total forecast errors should be located between the up spinning reserve and down spinning reserve, because these two reserves are calculated considering only one standard deviation. Different numbers of standard deviations in the spinning reserve calculation could be considered, depending on the risk aversion of the system operator.

This methodology allows to model, quantify, analyze and verify the security scheme required by a microgrid. The security scheme ensures efficiently the frequency stability of the microgrid, after the occurrence of events associated with forecast errors in both the electricity demand and the power availability of the PVGs.

The proposed methodology was applied on a real microgrid located at the Universidad Nacional de Colombia's campus (latitude 04°38' N, longitude 74°05' W and elevation 2556 m.a.s.l.). This microgrid is described below.

III. DESCRIPTION OF THE MICROGRID

The microgrid [10] is a low voltage system (208/120V) connected to the existing electricity distribution network. This grid considers, among others, a distributed generator, AC loads, computer applications, a real-time database system, bi-directional energy meter and a switching system. These elements allow to manage the energy resources under the scheme of microgrids, which promote the efficient use of the energy, improve the power quality, the reliability and the security, and increase the system flexibility.

The microgrid incorporates a PVG with a power capacity of 3640 Wp, that maintains the concept of BIPVS (Building Integrated Photovoltaic Systems). The PVG is coupled to two phases of the microgrid due to its two-phase output condition, which is standard for this type of small-scale generation. This PVG uses an electronic power inverter to connect it to the AC electric network.

The microgrid considers the strategic installation of meters, which allow to register the dynamic behavior of bi-directional power flow caused by the DG introduction in this grid. The measurement scheme is presented in Fig. 1.

The microgrid also has an automation system composed by a monitoring and a control system. This automation system allows to register voltage, power and frequency to perform control strategies, which will permit in the future the assignment of energy resources based on technical and economic considerations.

IV. IMPLEMENTATION OF THE PROPOSED METHODOLOGY

For implementing the proposed methodology, it was first analyzed and forecast the electricity demand and the power availability of the PVG. From this information, the spinning reserve required by the microgrid was determined and validated.

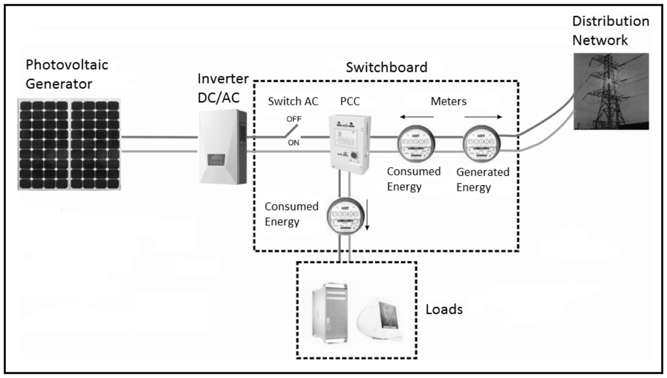

Fig. 1. Microgrid located at the Universidad Nacional de Colombia's campus.

A. *Load analysis*

Initially, it was necessary to acquire and analyze the available historical data of the electricity demand in the microgrid. For that, a database of demand information recorded every hour along the last trimester of the year 2012 was obtained. This database only considers 12 of the 24 hours of a day (from 6:00 to 17:59), because during this period there is significant electricity consumption in the microgrid.

From this database, it was possible to model the behavior of the demand, to forecast its availability and to identify the up and down standard deviation in its forecast, at each study hour of the next day. This was realized using the time series technique based on structural models [9].

The results of the load analysis are presented in Fig. 2.

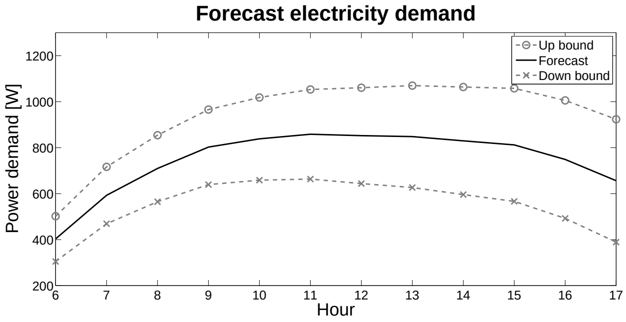

Fig. 2. Forecast electricity demand in the microgrid.

The Fig. 2 allows to analyze the forecast demand (FD), which is represented by the solid line. This figure shows that the FD for the next day starts with a value of 403.28 W at the hour 6. This value increases to 858.23 W at the hour 11. Finally, the FD decreases to a value of 656.33 W at the hour 17.

The Fig. 2 also shows the up and down standard deviation bounds in the forecast demand, which are represented by the dotted lines. From these bounds, it was possible to analyze that the up and down standard deviation in the forecast demand ($USDD$ and $DSDD$) increase their amplitude as the forecast horizon becomes larger, i.e. the forecast uncertainty increases as the forecast period becomes larger. The $USDD$ and $DSDD$ start with a value of 98.52 W at the hour 6. This value increases to 267.13 W at the hour 17.

It is important to note that this standard deviation is symmetric, i.e. the up standard deviation is the same as the down standard deviation.

B. *Generation analysis*

First of all, it was necessary to acquire and analyze the available historical data of the solar radiation and temperature in the area where the PVG is located. For that, a database of weather information recorded every hour along the year 2012 was obtained. This database only considers 12 of the 24 hours of a day (from 6:00 to 17:59), because during this period there is significant solar radiation.

From this database, it was possible to model the behavior of the solar radiation and temperature, to forecast their availability and to identify the up and down standard deviation in their forecast, at each study hour of the next day. This was realized using the time series technique based on structural models [9].

The results of the solar radiation analysis are presented in Fig. 3.

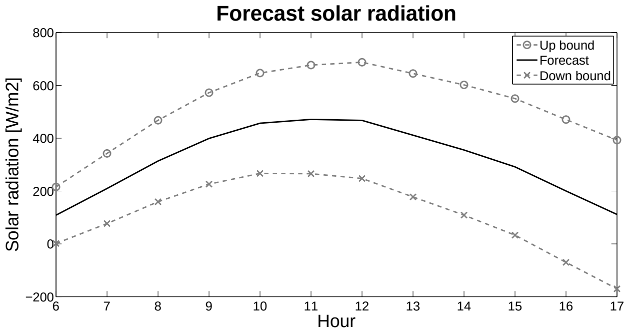

Fig. 3. Forecast solar radiation in the area where the PVG is located.

The Fig. 3 shows that the forecast solar radiation for the next day starts with a value of 108.56 W/m^2 at the hour 6. This value increases to 471.31 W/m^2 at the hour 11. Finally, the forecast solar radiation decreases to a value of 111.31 W/m^2 at the hour 17.

The Fig. 3 also allows to analyze that the up and down standard deviation in the forecast solar radiation increase their amplitude as the forecast horizon becomes larger. The up and down standard deviation start with a value of 107.05 W/m^2 at the hour 6. This value increases to 281.40 W/m^2 at the hour 17.

The results of the temperature analysis are presented in Fig. 4.

The Fig. 4 shows that the forecast temperature for the next day starts with a value of 7.35 °C at the hour 6. This value increases to 18.63 °C at the hour 11. Finally, the forecast temperature decreases to a value of 10.81 °C at the hour 17.

The Fig. 4 also allows to analyze that the up and down standard deviation in the forecast temperature increase their amplitude as the forecast horizon becomes larger. The up and down standard deviation start with a value of 2.70 °C at the hour 6. This value increases to 7.08 °C at the hour 17.

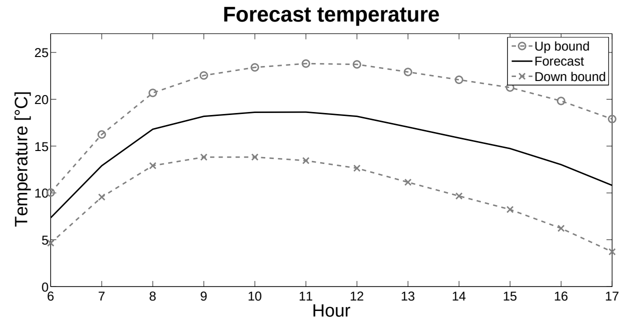

Fig. 4. Forecast temperature in the area where the PVG is located.

Next, the electric behavior of a PVG was modeled using MATLAB. For that, it was used the mathematical model of this generator proposed in [11].

Then, the technical parameters of the PVG interconnected to the microgrid were identified [11]. These parameters are described in Table I.

Parameter	Range
Module	KC 130
Generator power	3640 Wp
Modules in series	14
Branches in parallel	2
Total modules	28
Generator open circuit voltage	306.6 V
Generator maximum power voltage	264.4 V
Generator short circuit current	16.04 A
Inverter (xantrex)	3100W

TABLE I
PARAMETERS OF THE PVG INTERCONNECTED TO THE MICROGRID.

Afterwards, it was possible to forecast the power availability of the PVG interconnected to the microgrid and to identify the up and down standard deviation in its forecast, at each study hour of the next day. This was realized using the mathematical model of a PVG, its technical parameters and the hourly forecast of its primary resources (solar radiation and temperature). The results of the generation analysis are presented in Fig. 5.

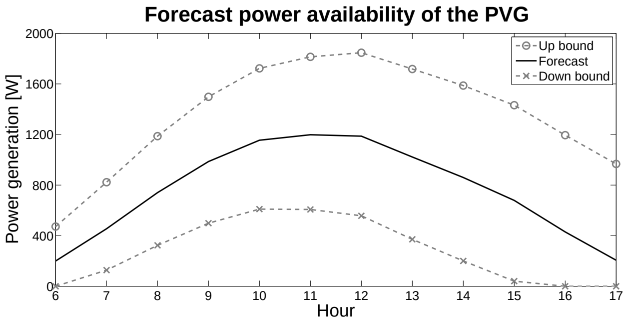

Fig. 5. Forecast power availability of the PVG interconnected to the microgrid.

The Fig. 5 shows that the forecast power availability of the PVG (FP) for the next day starts with a value of 199.71 W at the hour 6. This value increases to 1197.80 W at the hour 11. Finally, the FP decreases to a value of 205.40 W at the hour 17.

The Fig. 5 allows to analyze that the up standard deviation in the forecast power availability of the PVG ($USDP$) increases its amplitude as the forecast horizon becomes larger. The $USDP$ starts with a value of 272.01 W at the hour 6. This value increases to 761.60 W at the hour 17.

The Fig. 5 also allows to analyze that the down standard deviation in the forecast power availability of the PVG ($DSDP$) increases its amplitude as the forecast horizon becomes larger. However, it starts to decrease its amplitude from the hour 15. The $DSDP$ starts with a value of 199.71 W at the hour 6. This value increases to 659.89 W at the hour 14. Finally, the $DSDP$ decreases to a value of 205.40 W at the hour 17.

The decreasing behavior of the $DSDP$ at the last forecast hours is due to two aspects: The down standard deviation bound in the forecast solar radiation has negative values at the last forecast hours; the mathematical model of the PVG interconnected to the microgrid support negative values of neither solar radiation nor temperature. These two aspects led to represent the down standard deviation bound in the forecast power availability of the PVG with a value of zero, at those hours where the down standard deviation bound in the forecast solar radiation is lower than zero.

It is important to note that the standard deviation in the forecast power availability of the PVG is asymmetric, i.e. the up standard deviation is different to the down standard deviation.

C. Security analysis

From the load and generation analysis, it was determined the up and down spinning reserve required by the microgrid, at each study hour of the next day. The results of the security analysis are shown in Table II.

Hour	USDD	DSDP	USR	DSDD	USDP	DSR
6	98.52	199.71	**222.69**	98.52	272.01	**289.30**
7	123.60	327.46	**350.01**	123.60	367.85	**388.06**
8	144.68	416.89	**441.28**	144.68	446.43	**469.29**
9	163.18	487.30	**513.90**	163.18	511.85	**537.23**
10	179.74	544.87	**573.75**	179.74	568.08	**595.84**
11	194.83	590.66	**621.96**	194.83	616.38	**646.44**
12	208.57	629.60	**663.24**	208.57	659.95	**692.12**
13	221.58	650.95	**687.63**	221.58	695.65	**730.09**
14	234.00	659.89	**700.15**	234.00	727.19	**763.92**
15	245.71	638.52	**684.16**	245.71	753.18	**792.25**
16	256.55	429.49	**500.28**	256.55	765.15	**807.02**
17	267.13	205.40	**336.97**	267.13	761.60	**807.09**

TABLE II
SPINNING RESERVE REQUIRED BY THE MICROGRID.

The Table II shows the up standard deviation in the forecast demand ($USDD$) and the down standard deviation in the forecast power availability of the PVG ($DSDP$). With these two variables, it was possible to calculate the up spinning reserve (USR), using the equation (1). The USR starts with a value of 222.69 W at the hour 6. This value increases to 700.15 W at the hour 14. Finally, the USR decreases to a value of 336.97 W at the hour 17.

This table also shows the down standard deviation in the forecast demand ($DSDD$) and the up standard deviation in the forecast power availability of the PVG ($USDP$). With these two variables, it was possible to calculate the down spinning reserve (DSR), using the equation (2). The DSR starts with a value of 289.30 W at the hour 6. This value increases to 807.09 W at the hour 17.

The USR and DSR allows to counter the uncertainty in both the electricity demand and the power availability of the PVG interconnected to the microgrid.

D. Validation analysis

To validate the proper sizing of the up and down spinning reserve, it was necessary to acquire and manage both the real electricity demand in the microgrid (RD) and the real power availability of the PVG interconnected to the microgrid (RP), at each study hour.

From this information, it was possible to made a comparative analysis between the RD and the forecast demand (FD). The results of this analysis are presented in Fig. 6.

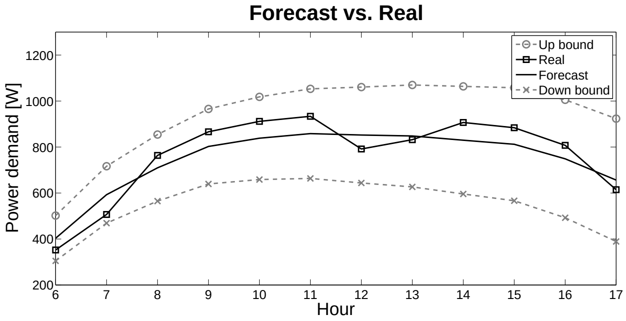

Fig. 6. Forecast demand vs. Real demand.

The Fig. 6 shows that the RD behavior is located within the standard deviation bounds in the forecast demand, during the whole forecast horizon.

These results allowed to verify that the time series technique used represents in a very proper way the demand due to the characteristic behavior of this variable.

Moreover, it was possible to made a comparative analysis between the RP and the forecast power availability of the PVG (FP). The results of this analysis are presented in Fig. 7.

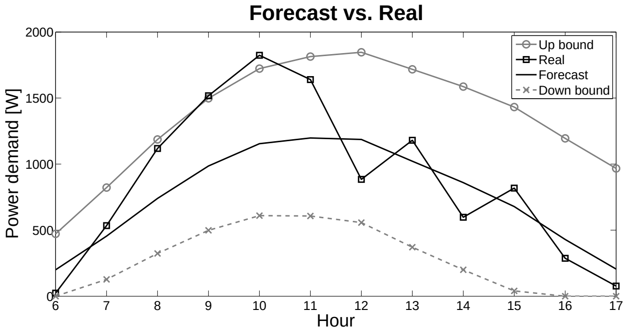

Fig. 7. Forecast power availability vs. Real power availability of the PVG.

The Fig. 7 shows that the RP behavior is located within the standard deviation bounds in the forecast power availability of the PVG, during much of the forecast horizon. However, the RP exceeds the up standard deviation bound at the hours 9 and 10 in 19.93 W and 101.01 W, respectively.

These results allowed to verify that the time series technique used represents in a proper way the primary resources of the PVG (solar radiation and temperature). However, it was really difficult to forecast these variables with high precision due to the high stochastic behavior of them.

The comparative analysis presented in Fig. 7 and Fig. 6 allowed to determine the forecast errors in both the electricity demand and the power availability of the PVG. The results of this analysis are presented in Table III.

Hour	FD	RD	ED	FP	RP	EP
6	403.28	352.18	**-51.10**	199.71	23.16	**176.56**
7	592.75	506.68	**-86.07**	454.63	534.33	**-79.70**
8	709.56	763.47	**53.91**	740.27	1118.29	**-378.01**
9	802.47	866.29	**63.82**	985.91	1517.68	**-531.78**
10	838.41	911.73	**73.32**	1154.66	1823.76	**-669.10**
11	858.23	933.53	**75.30**	1197.80	1640.05	**-442.26**
12	852.16	791.61	**-60.55**	1186.75	884.39	**302.35**
13	848.19	832.05	**-16.14**	1021.95	1180.29	**-158.34**
14	829.74	906.82	**77.08**	859.77	597.82	**261.95**
15	812.09	883.99	**71.90**	678.63	818.39	**-139.76**
16	748.82	807.43	**58.61**	429.49	287.07	**142.41**
17	656.33	614.56	**-41.77**	205.40	76.59	**128.81**

TABLE III
FORECAST ERRORS IN BOTH THE DEMAND AND THE POWER AVAILABILITY OF THE PVG.

The Table III shows the forecast demand (FD) and the real demand (RD). With these two variables, it was possible to calculate the forecast errors in the demand (ED), using the equation (3). These errors reached a maximum value of 86.07 W at the hour 7.

This table also shows the forecast power availability of the PVG (FP) and the real power availability of the PVG (RP). With these two variables, it was possible to calculate the forecast errors in the power availability of the PVG (EP), using the equation (4). These errors reached a maximum value of 669.10 W at the hour 10.

From the ED and EP presented in Table III, the total forecast errors (E) were determined, using the equation (5). The results of the validation analysis are presented in Table IV.

Hour	E	USR	DSR
6	125.46	222.69	289.30
7	-165.77	350.01	388.06
8	-324.10	441.28	469.29
9	-467.96	513.90	537.23
10	-595.78	573.75	595.84
11	-366.96	621.96	646.44
12	241.80	663.24	692.12
13	-174.48	687.63	730.09
14	339.03	700.15	763.92
15	-67.86	684.16	792.25
16	201.02	500.28	807.02
17	87.04	336.97	807.09

TABLE IV
TOTAL FORECAST ERRORS.

The Table IV shows that E is lower than USR for positive values of E, which is in accordance with equation (6). This table also shows that $|E|$ is lower than DSR for negative values of E, which is in accordance with equation (7).

It is important to note that the RP has a significant increase in its value with respect to the FP at the hours 9 and 10. However, the RD also increases its value with respect to the FD at these hours. This led to the E does not exceed the DSR at these hours.

The behavior of E at each study hour can be clearly observed in Fig. 8.

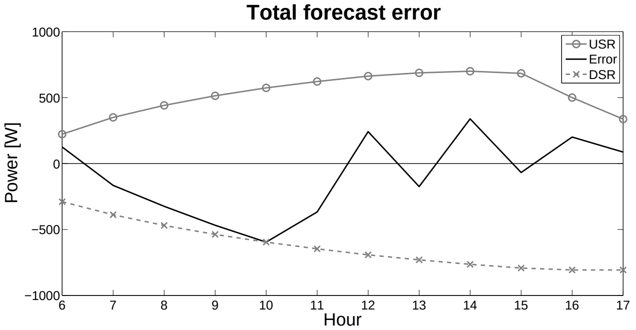

Fig. 8. Behavior of the total forecast error.

The Fig. 8 shows that the E is located within the security bounds represented by the USR and DSR, during the whole forecast horizon. The security scheme designed allowed to ensure the frequency stability of the microgrid at each study hour, after the occurrence of events associated with forecast errors in both the electricity demand and the power availability of the PVG.

V. CONCLUSIONS

The main contribution of this paper is the development of a methodology which allows to model the security scheme required by a microgrid that considers the participation of intermittent energy sources, such as PVGs. The security scheme is represented by an up and down spinning reserve located in the generators of the microgrid with controllable power output.

The methodology consists of performing a four stages analysis at each study hour of the next day: a load analysis, which evaluates the uncertainty in the forecast electricity demand; a generation analysis, that evaluates the uncertainty in the forecast power availability of the PVGs; a security analysis, which quantifies and evaluates the up and down spinning reserve required by the microgrid to ensure the frequency stability; and a validation analysis, that verifies the proper sizing of the up and down spinning reserve.

To implement the proposed methodology, it was evaluated a forecasting technique based on structural models, using the statistical software OxMetrics 6.3 - module STAMP.

The proposed methodology was implemented on a real microgrid located at the Universidad Nacional de Colombia's campus. From this, it was concluded that the time series technique used represents in a proper way the electricity demand and the primary resources of the PVG (solar radiation and temperature).

It was also concluded that the security scheme designed for the microgrid allowed to ensure efficiently the relation between generation and demand at each study hour, after the occurrence of events associated with forecast errors in both the electricity demand and the power availability of the PVG.

It is clear that the interconnection of PVGs in a microgrid significantly changes the security conditions of this grid, but it is a challenge for the near future that must be assumed and evaluated with appropriate methodologies to ensure the frequency stability.

VI. ACKNOWLEDGMENT

The authors would like to thank the SILICE group, Universidad Nacional de Colombia, for their support and suggestions. The authors would also like to thank the statistical consulting group for their invaluable assistance in the time series analysis.

REFERENCES

[1] L. Luna, E. Parra, *"Methodology for assessing the feasibility of interconnecting distributed generation"*, IEEE PES PowerTech, Trondheim - Norway, Jun. 2011.

[2] L. Luna, E. Parra, *"Methodology for assessing the impacts of distributed generation interconnection"*, Engineering & Research Journal, Vol. 31, No. 2, pp. 36-44, Nov. 2011.

[3] N. Hatziargyriou, H. Asano, R. Iravani, C. Marnay, *"microgrids"*, IEEE Power & Energy Magazine, Vol. 5, No. 4, pp. 78-94, Jul. Aug. 2007.

[4] IEEE Smart Grid Research, *"IEEE Vision for smart grid controls: 2030 and beyond"*, Institute of Electrical and Electronics Engineers, ISBN: 978-0-7381-8458-6, 2013.

[5] Standard IEEE 1547.4, *"IEEE guide for design, operation, and integration of distributed resource island systems with electric power systems"*, IEEE Standards Coordinating Committee 21 on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage, Jul. 2011.

[6] M. Ortega-Vazquez, D. Kirschen, *"Optimizing the Spinning Reserve Requirements Using a Cost/Benefit Analysis"*, IEEE Transactions on Power Systems, Vol. 22, No. 1, Feb. 2007.

[7] M. Ortega-Vazquez, D. Kirschen, D. Pudjianto, *"Optimising the scheduling of spinning reserve considering the cost of interruptions"*, IEE Proc.-Gener. Transm. Distrib., Vol. 153, No. 5, Sep. 2006.

[8] M. Wang, H. Gooi, *"Spinning reserve estimation in microgrids"*, IEEE Transactions on Power Systems, Vol. 26, No. 3, Aug. 2011.

[9] H. Lutkepohl, *"New Introduction to Multiple Time Series Analysis"*, Springer Berlin Heidelberg New York, ISBN: 3-540-40172-5, 2005.

[10] J. Hernández, L. Luna, A. Blanco, *"Design and installation of a smart grid with distributed generation. A pilot case in the Colombian networks"*, IEEE Photovoltaic Specialists Conference, Austin - Texas, Jun. 2012.

[11] J. Hernández, G. Gordillo, W. Vallejo, *"Predicting the behavior of a grid-connected photovoltaic system from measurements of solar radiation and ambient temperature"*, Applied Energy Journal, Vol. 104, pp. 527-537, Apr. 2013.