Solar Generation Estimation in Electric Power Systems for Prospective Frequency Control Studies

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ABSTRACT: Increasing the presence of non-conventional clean energy sources in Electrical Power Systems (EPS) is a global strategic goal. Particularly, photovoltaic systems are attractive due to their versatility, low maintenance cost, easy installation, noiselessness, etc. However, the integration of photovoltaic systems into EPS increases the necessary regulation actions performed by system generators due to stochastic fluctuations of solar radiation, especially on cloudy days. Even using complex models that consider many variables, solar irradiation and its corresponding photovoltaic power generation are difficult variables to forecast with accuracy in cloudy day scenarios. To address this problem, Energy Storage Systems (BESS) have been proposed as a solution to mitigate the variability of photovoltaic generation, which reduce the need to use traditional spinning reserves and provide auxiliary grid services. The BESS selection required to mitigate photovoltaic generation is directly related to the worst-case daily variability of photovoltaic generation in the short term. This paper proposes a practical estimation of daily perspective photo voltage solar generation curve in Electrical Power Systems.

1 INTRODUCTION

There is currently a growing trend towards the introduction of photovoltaic and wind power plants in Electric Power Systems (EPS). This responds to the need to replace conventional units that use fossil fuels, as a measure to reduce the growing environmental pollution and its depletion. However, solar generation has an inherently intermittent character, due to solar irradiation behavior incident on the panels [1-4].

Two causes can be distinguished in solar daily irradiation pattern. The first one corresponds to the diurnal variation cycle and the second one is related to local effects caused by rapid low clouds movement over the panels [2-5]. Large variations in solar irradiance due to the first cause are easily predictable and relatively slow, typically less than 1%/min, while those due to the second cause can reach values greater than 10%/min and are difficult to forecast [1]. The beginning and end of shadows, due to these clouds, cause large variations in solar irradiation incident on the photovoltaic panels. This can be detrimental to their operation, not allowing them to follow the maximum power point programmed in their work algorithm (MPPT), as well as causing rapid active power imbalances in the system to which they are connected, with frequency deviations from their nominal values, negatively affecting the quality of the energy delivered to the system, as well as their safe operation.

The increasing penetration of generation from renewable energy sources, especially solar, significantly amplifies the problems mentioned above and is therefore a reason for research aimed at

promoting quality regimes and safe system operation [5]. In many countries, restrictions have been established to control power fluctuations of grid-connected photovoltaic power plants to ensure the reliability and quality of the generated active power. An example of the above statement is the case of Puerto Rico, where a maximum limit of photovoltaic power generated variation has been established in 10% of their nominal capacity per minute [6]. Similarly, in Germany, transmission grid operators have imposed a ramp variation limit of 10% per minute like the case of Puerto Rico [6].

Multiple studies have measured, by means of irradiation sensors, the variability of irradiation in photovoltaic power plants, proving that it can vary more than 50% of its nominal values in 1 second intervals [7-8]. This makes the use of BESS energy storage sources necessary to satisfy the constraints of ramp variations of generated power in different countries, since conventional units are not capable of varying their generation in such small-time intervals with the necessary speed. Furthermore, BESS function is to reduce the ramp variations in either direction of photovoltaic power generation plants to the stipulated values [9].

The effect of solar radiation variability on photovoltaic power plants is different when analyzing a single plant or a set of plants distributed in a certain region. Previous studies have been reported in different scenarios that when a set of plants is considered, there is a strong effect of generated power variability reduction, which is called "smoothing effect" [7-10]. This effect derives from the typical cloud dimensions (1-10 Km) and its velocity.

The variability reduction (*VR*) is defined in [10] as the ratio between the variances calculated at a present time interval according to the expression:

$$VR = \frac{\sigma_{\Delta t}^1}{\sigma_{\Delta t}^T} \qquad (1)$$

where $\sigma^1{}_{\Delta t}$ is the generated power variance in a photovoltaic power plant in the time interval Δt; $\sigma^T{}_{\Delta t}$ is the total generated power variance in the set of photovoltaic power plants in the time interval Δt.

Studies reported in [10] for time intervals of 10 minutes show that variability reduction ranges from 1.7 to 3.3 times. The study period was 1 year. In similar studies [1], performing calculations in 5-minute intervals, in one year period, report values between 2.4 and 4.1. This shows that the variability depends on considered time interval. The longer the time interval, the smaller the reduction of variability, i.e., the smaller the flattening effect of the generated power. In [12-13] it is shown that, with no correlation between generated photovoltaic plants powers, variability of a set *N* of farms can be calculated as:

$$\sigma_{\Delta t}^T = \frac{\sigma_{\Delta t}^1}{\sqrt{N}} \qquad (2)$$

The correlation between the powers generated by the set of farms will depend on the geographical separation between their locations. In [14] it is shown

that the correlation coefficient between photovoltaic farms decreases as the distance between their locations increases. In [15] it is established that in order to perform perspective calculations it is of utmost importance to estimate the maximum variation of the generated power of the future set of farms, considering their locations and the corresponding flattening effect of the summary generation, to avoid oversizing BESS capacities of necessary units for an effective frequency control under these conditions, with the corresponding economic effects. In [16] it is verified that high values of irradiance variation, measured by sensors in photovoltaic generation plants in small time intervals, are not reflected in similar values of power variations in the complete plant or to sets of plants, which could be impacting in system behavior.

What would be then the time intervals that should be considered, to estimate power variation in photovoltaic power plants, to determine their interaction with the system to which they are connected and therefore their influence on frequency control?

In [16] it is stated that time intervals depend on the type of study to be executed, for the case of frequency regulation studies the intervals would be in the order of seconds to minutes. In the case of load covering studies, the intervals to be analyzed correspond to tens of minutes and in the case of economic dispatch and planning of electric power systems, the variability associated with the diurnal cycle is the necessary to be considered.

To estimate BESS nominal values, (Power and Energy), necessary to perform primary and secondary control of frequency, with important increases of photovoltaic penetration, it is necessary to start from perspective estimates of photovoltaic power generated in the days of greater variations, where intervals of several seconds to minutes are considered. This implies starting from current simultaneous measurements of power in existing installations that have a sampling time of at least one second. From these measurements it is possible to estimate the future behavior when solar photovoltaic penetration in the system increases. The estimation must consider the flattening effect of the photovoltaic generation, the existence or not of correlation between different plants generated power, as well as different climatic seasons during the year and the possible variations from one year to another. Similar calculations must be made for wind power plants if the total installed power does not allow to disregard the variations caused by the randomness of the wind in perspective calculations.

From these calculations and using concentrated models of the considered power system [17-18], it is possible to estimate BESS nominal values that ensures an adequate frequency performance. In these models, photovoltaic and wind generated powers should be included, by means of "lookup" tables during the days of greater variability in intervals of the order of one second. In analyzed works, studies are reported to select BESS nominal values that globally compensate active power variations resulting from an important penetration of photovoltaic power plants. The

selection criterion, under these conditions, is the system frequency behavior.

In the present work, daily average solar power generation curve is estimated in per unit (p.u.) with respect to installed capacity under 2030 system conditions. For this purpose, it is necessary to assume that it´s shape is like that of the current average curve of maximum daily variations obtained from database processing of years 2019 and 2020. In subsequent works, estimates of Cuban System frequency behavior for different nominal values of BESS will be presented.

The present work is structured as follows. Section II presents information of processing tool required to estimate photovoltaic generation in 2030. Section III presents the necessary requirements for BESS nominal values estimation. Section IV presents the estimated maximum daily solar generation curve and Section V presents conclusions.

2 PROCESSING TOOL DEVELOPMENT

In the Republic of Cuba, a significant penetration is planned for the coming years, bringing the generation by non-conventional plants to around 25% of the total generated power in 2030. To estimate the future behavior of the photovoltaic power generated in a daily cycle, considering its variation in intervals of several seconds to minutes, it is necessary to start from the information of the current generation performance in the system in different actual existing installations, which requires the processing of extensive databases. This is practically impossible if there are no computer programs developed for this purpose.

In Cuban Electrical System, power of most of the installed photovoltaic generation plants ranges between 4 and 6 MW and they are planned to be separated from each other by no less than 8 km to make the correlation between the generated powers negligible [19].

FREDAT V1.0 tool developed by the authors for this purpose is presented. This tool, based on simultaneous measurements of active power generated every second in different solar generation plants in the form of Excel tables, performs the following actions:
- Filters the database, eliminating erroneous values and making interpolations between values when losses of measurements are detected in the database.
- Determines the curves corresponding to the highest power variation observed on the day of the solar farm under study, on the days with the highest incidence of clouds, previously selected using adjustable length windows.
- From the set of solar farms under study in a day, the combination of solar farms with the highest and lowest generation variation corresponding to different combinations of a selected number of solar farms, as well as the summary power curve in one-second intervals. From these curves, an average variation power curve is obtained for the

analyzed day from the combinations with the highest and lowest variation.
- For adjustable time windows, curves of average power values are calculated, and from them the sum of power values above and below these average values, calculated as:

$$(P_i - P_m)\Delta t \tag{3}$$

where P_i is the instantaneous power and P_m is the mean value calculated using the adjustable window and Δt is the time interval between measurements. In this way it is possible to estimate the energy value during the day, necessary to cover the variability of the generated power with respect to the average values previously calculated.
- Maximum and minimum values of energy during the day are calculated for isolated farms or combinations of N farms previously selected in the main screen.

To better understand the performance of the developed tool, Figure 1 shows it main screen. The database must be stored in a folder with known address in Excel format. To start the work, the location of this folder must be placed in the upper left part of the screen.
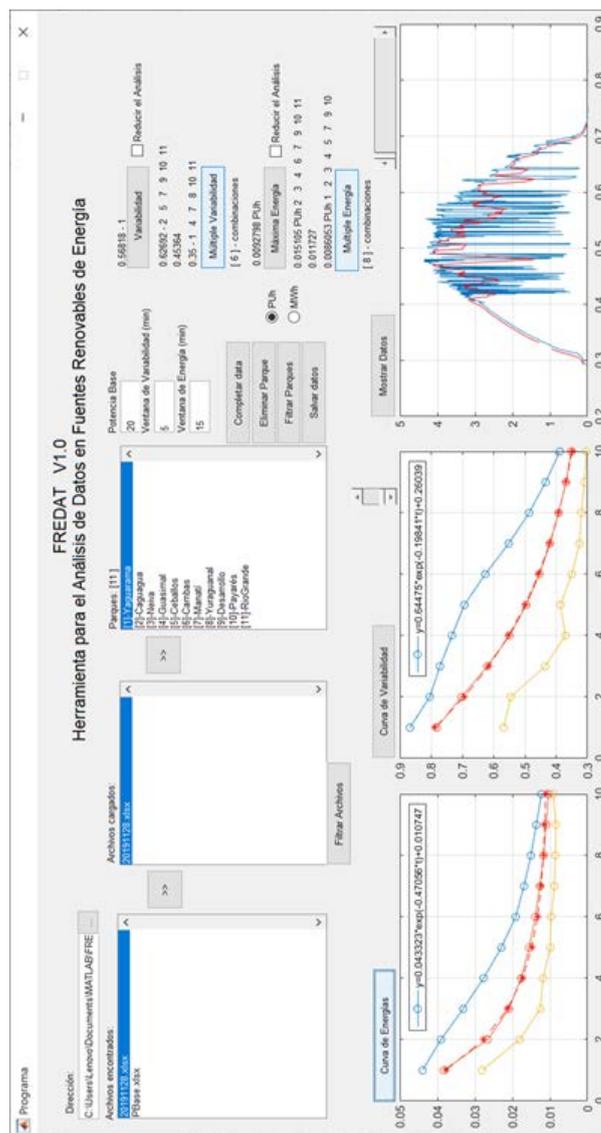

Figure 1. Main tool screen of FREDAT V1.0.

Next, all the files in the database are displayed, which are selected by clicking on the arrow and the files corresponding to generated powers during different days in the different PV plants of the system are loaded, which are listed in the third column by their names when analyzed day is selected.

The buttons in the fourth column allow selected plants deletion. The second button eliminates any errors that may exist in the database and fills in the missing measurement information by linear interpolation. The last button saves the database ready to start calculations.

Before starting it is necessary to set the common power base, because the farms have different powers, and it is necessary to take a common base. This is done in the space under the "Potencia Base" (Power Base) sign. Under the option "Ventana de variabilidad (min)" (Variability window (min)) the size of the window for the calculations is selected. If a farm is selected and the variability key is pressed, the result shown in Figure 2 appears for the selected farm, in this case 11, which corresponds to Santa Teresa Farm.
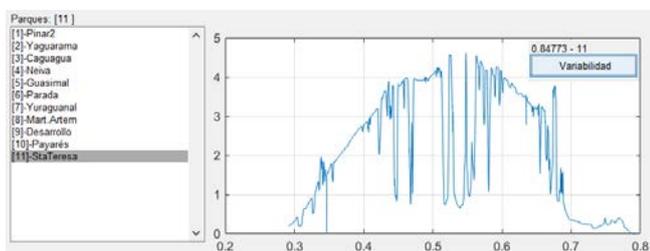

Figure 2. Power generated from Santa Teresa Farm.

Figure 3 shows how the program calculates the maximum variation, which in this case is by moving a 5-minute window over the database and calculating the maximum power variation in that window and updating it as the window moves through all the data so that at the end the highest generated power in the window for the selected generating plant on the day is selected.
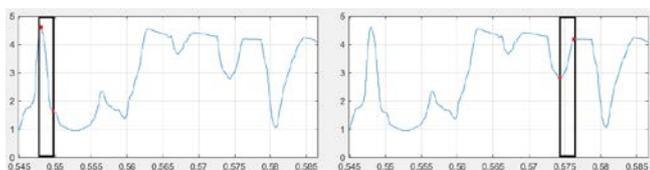

Figure 3. Calculation of the largest power variation by moving a 5-minute window over the data base.

To calculate the variation of several plants of the total number of plants loaded, click on the "Múltiple Variabilidad" (Multiple Variability) key and mark the number of plants to calculate this variation as shown in Figure 4.
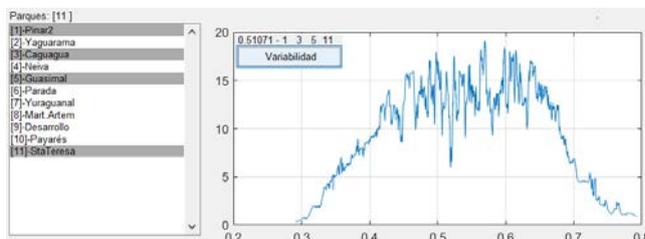

Figure 4. Maximum variation for combinations of four farms by 5-minute window movement over the database.

In this case, the maximum and minimum variation of four farms combinations are calculated from the set of 11 farms loaded in the program. The values of maximum variation in p.u. with respect to the capacity of the farms in the case of one farm is 0.847pu for the Santa Teresa Farm and in the case of four farms it is lower.

The above is the result of the flattening effect resulting in 0.51pu, corresponding to the farms Pinar 2, Caguagua, Guasimal and Santa Teresa, in the case of the four farms shown in Figure 4.

The program also calculates farms combination considered to cause the lowest power variation during the day as shown in Figure 5, for three farms combinations. From the curves of maximum and minimum variation calculates curve of average values of power variation.

In the case of three farms combinations, from the total of 11 farms in the database, 165 combinations are required to determine the group with maximum variation. In the case of five farms combinations, the number of required combinations for comparison reaches 462.

Figure 5. Minimum, mean and maximum variation for combinations of three generating plants from a database of 11 units.

The objective of processing the databases of the generating plants is to estimate the values of the highest power variation of a set of N plants that would work connected to the grid at a future date to estimate the nominal values of the BESS that could compensate these variations.

In multiple works [10-13] it is found that the maximum power variation of a set of plants decreases as the number of plants increases. In [20] it is established that an acceptable estimate of this variation can be estimated from successive operations for all combinations of plants in the data. Thus, it is possible to determine with sufficient accuracy the trend of the maximum power variations. Carried out calculations show that from a given number of farms in the data the results tend to practically the same values.

The developed tool provides this possibility by adjusting the trend of the maximum variation curve of the generated power as a function of the number of grouped farms, just by pressing the "Variability Curve" key. Figure 6 shows the results for groupings from 1 to 11 farms on a selected day. In this case, the values of the different groupings for the maximum power variation on the selected day is estimated as follows:

$$y = 0.66956 e^{(-0.36386t)} + 0.22119 \qquad (4)$$

where N is the corresponding number of grouped plats.

If the number of plants is large then it can be considered that the value of maximum variation of the generated power would correspond to the independent term of the equation 0.2212 p.u., which corresponds to 22.12% of N plants power connected to the system. The above can be seen in Figure 6 where the curves for minimum and average power variation for different groupings are also shown.
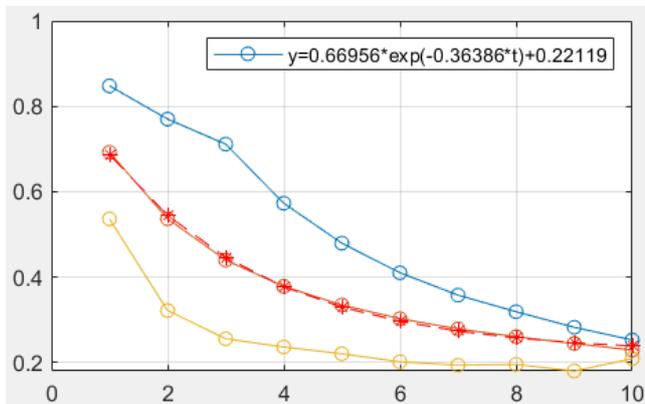

Figure 6. Results of the perspective calculation of the variation of the generated power for the case of 10 plants connected to the system for the selected day.

Days with the highest variability in the year(s), are selected as the initial database, see Table I in Appendix. Maximum power variation will be an upper limit to be considered for necessary BESS nominal values to compensate these power variations. For the above-mentioned reasons, it is possible to know the average values so that the specialist can decide the values to be considered in BESS selection. In the case of the energy necessary values to compensate the power variations around the average are calculated with 15-minute windows, the program looks for the sum of the instantaneous powers that exceed or not this average value to then calculate the energies delivered or consumed with respect to this average value and the sum of these accumulated energies, each one with its sign allow us to estimate the maximum energy that a BESS would produce to compensate for the power variations of the photovoltaic plants.

Figure 7 shows this procedure graphically, where the red curve represents the average values and below the red areas correspond to the energy consumed by the BESS and in blue the energy that should be delivered. The values of interest would be the

maximum accumulated values during the day, consumed or delivered.
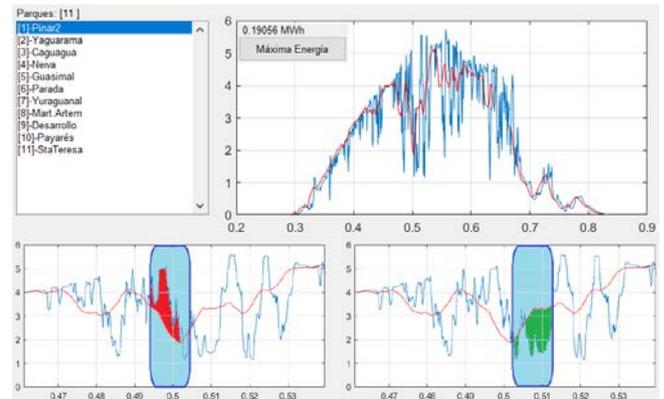

Figure 7. Maximum energy calculation process to cover variations in power generated by photovoltaic plants.

Similar procedures can be performed for different combinations of farms working with the total generated power and proceed in a similar way as in the case of calculating the maximum variation of the power when N plants are tended. Figure 8 shows the results.
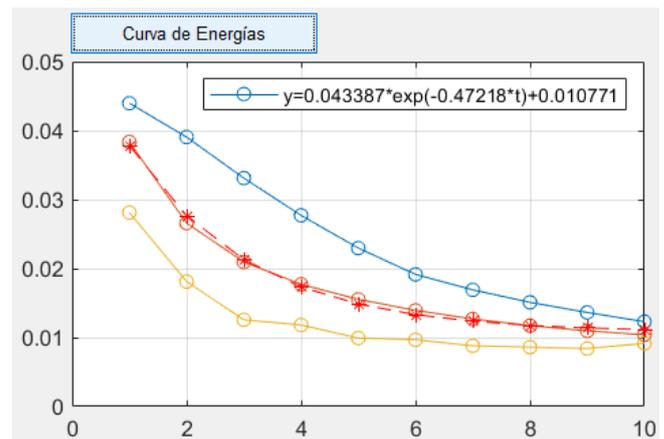

Figure 8. Energy trend as a function of number of plants.

3 REQUIREMENTS FOR BESS NOMINAL VALUES SELECTION

The BESS used in frequency control must not only compensate the variability of the power generated by the photovoltaic plants but also be able to, in cases of important active power deficits in the system, maintain the frequency at acceptable values until measures can be taken to restore the normal working regime of the system, and this condition is usually the one that determines the energy values of the BESS required to be implemented in the system [20].

To reliably select the nominal values of the BESS in [19] it is established that it is necessary to take into account: Considerations related to the lifetime of the battery, such as Depth of Discharge (DoD), temperature, life cycle as well as other aspects such as its efficiency and the requirements of its behavior in the system.

Among these requirements are:

- Perform primary and secondary frequency control by limiting the participation of conventional units only at times when large power unbalances are generated. This is possible by adjusting dead bands in the BESS lower than those of conventional units and adjusting lower droops in their active power controls.
- Decrease the primary and secondary regulation reserves of the conventional units, favoring their efficient work and increasing the planned maintenance intervals.
- In case of sudden departures of generating units, it must be able to maintain acceptable frequency values for a sufficient period so that measures can be taken for tertiary frequency control or decision making by the operators to restore the working regime to safe conditions.

To verify compliance with all these considerations, it is necessary to model system behavior under working conditions that are estimated to occur in the future, using simplified concentrated models of the generators, the BESS and its controls, the predicted daily load curve, the curves of the total power generated by all the photovoltaic and wind power plants in one second intervals, which would be connected to the system at the analyzed time.

4 DAILY PHOTOVOLTAIC GENERATION CURVE ESTIMATION FOR THE YEAR 2030

In the case of the Cuban System, it is projected that by the year 2030 the solar installed capacity will be around 2000MW. To check the behavior of the frequency using BESS of different nominal values, it is necessary to study the behavior of its load state during the day, which avoids the decrease of its lifetime.

For important capacities of solar generation, curves of this generation must be obtained by similar procedures using solar generation databases. The question to answer then would be:

What would be the maximum power variation in MW of N farms whose installed power is 2000MW and from this the summary power curve every second?

Maximum variation estimated processing measurements from six photovoltaic farms was 0.3232pu, and its trend for many farms is 0.251pu. If the base taken to make the current power sums was 20MW, this maximum variation can be estimated as:

$$P_{\max} = \left(\frac{2000 \times 0.251}{0.3232} \right) \times \frac{20}{32.48} \qquad (5)$$

where the factor 20/32.48 reduces the values to p.u. with respect to the capacity of the six farms and the factor 0.251/0.3232 considers the flattening of the maximum variation when the number of farms tends to a large number.

If we multiply the graph of average generated power of the six farms in p.u. in the day based on their sum power by the factor seen above, we will have the generated power estimation when there is an installed capacity of 2000MW. The results obtained from the above estimation in the interval from 7am to 7pm are shown in Figure 9. Maximum power variation in 5-minute window in the analyzed case is in the order of 500MW.
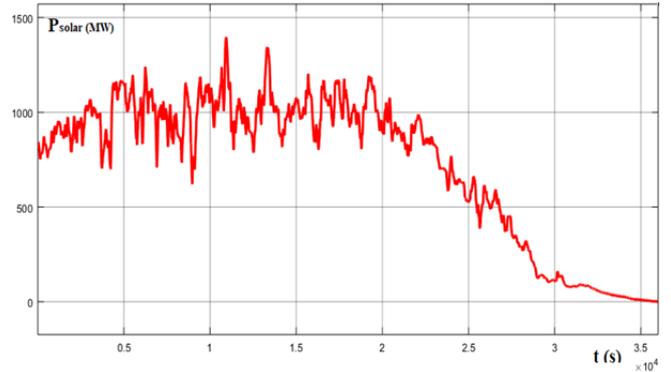

Figure 9. Estimated solar generation curve (7am-7pm) with maximum power variations in the Cuban "Sistema Electroenergético Nacional" (National Power System) in 2030.

This does not mean that the BESS should have a capacity of 500MW because it represents a higher value. To estimate more reliable values it is necessary, using concentrated models of the system, and the curves of solar and wind generation in 1 second intervals, to check the behavior of the frequency for different nominal values of the BESS, as well as the time that can maintain the reliable work of the system before critical conditions of outputs of generating units, with the objective of allowing the operator to make decisions for system recovery.

5 CONCLUSIONS

The computational tool developed allows, from a database of current simultaneous measurements of the power generated in photovoltaic units, to project into the future to estimate the maximum variation of this generation in the day, knowing the total installed power, as well as the estimation of the curve of greater variations of power generated in the day.

This curve is necessary for the selection of the BESS that meets all the requirements for its use in frequency control in the system. In order to verify the above, modelling is required to verify the fulfilment of these requirements, which will be the subject of future works.

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