Location of Quality Parameters in Small Smart Grid: Off-Grid Case Using Wavelet Transform

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Abstract. In the following work the analysis made to an electrical signal by means of wavelet toolbox will be shown. The analysis will be done contemplating the use of the Discrete Wavelet Transform (DWT). This will show the multilevel decomposition taking into account different orders of daubechies. Taking into account the different levels it is expected to show the variants in terms of energetic quality such as sag, swell and harmonic detection. The final work will link the work of digital signal processing with previous work where the construction of a prototype solar system will be explained to obtain the electrical signals of voltage, current and power consumed. In this introductory stage will show the step-by-step development that was taken into account to carry out the design and construction of a small grid scale prototype with AC and DC load control through the HMI interface with LabVIEW software. The design process of the off-grid solar system was carried out through 7 stages that framed the scale of the solar installation. Once the design of the sizing was finished, programming was carried out in Human Machine Interface (HMI) graphics environment with LabVIEW software for optimal control of AC and DC variable loads. This control was established through current relays from 5 volts to 110 volts AC and 5 volts to 12 volts DC. The control interface was made through an embedded board with NI-VISA communication. It is important to note that the smart grid control prototype "Smart Grid" shows optimal results in its operation; denoting this that from the optics of the programming done in the graphics environment, the control of loads dependent on control center’s act at disposition. Redundant this in improvements for the energy consumption derived from the storage system under the autonomy designed for three days.

1. Introduction
Smart grids. Are electrical networks that together can have information, communication and control technologies, in order to interconnect and operate a system efficiently. Inviting system users to be part of the production chain and not just as a consumer. If not as an entity capable of becoming self-generating and thus be able to provide their own energy and if possible their surplus inject them into the network if it is connected to the network. The matrix of change of the technology that the smart grids carry does not only contemplate the fact of connecting, monitoring and having the best domotic for the control through communications. It is also about the change of culture that we must have if we want to
disconnect from the network and stop consuming through common marketers or distributors. It is a change of mentality that will make you a citizen of the smart grids.

There are many theories, entities and authors that can emit a smart grid concept. According to Hassan Farhangin the electrical power industry is undergoing rapid change and he have talked about the path of smart grid in 2010 [1].

According to Vehbi C. Gungor, et al. The smart grid can be considered as a modern electric power grid infrastructure for enhanced efficiency and reliability through automated control [2].

According to Xi Fang, Satyajayant Misra, Guoliang Xue and Dejun Yang. The idea was raised that the smart grid was considered as the network of the new generation and that it could use bi-directional flows of energy and information to create an automated electrical network [3].

Authors like Maria Lorena Tuballa and Michael Lochinvar Abundob, in the review of the development of smart grid technologies present an overview of the smart grid with its general features, functionalities and characteristics [4].

Currently Colombia has an energy matrix with generation of hydraulic type, thermal with a.c.p.m, thermal with carbon, thermal with combustoleo, gas, and thermal with Jet-A1. _Co- generators with generation based on bagasse, carbon, gas, wind generation and solar generation. Showing a net effective capacity of 16856 MW.

Currently in Colombia the policies and regulatory changes have allowed to advance in types of initiatives that contemplate the use of photovoltaic solar energy. In reference [5], resolution issued by the commission of energy and gas regulation CREG 030 of 2018. By which the activities of small-scale self-generation and distributed generation in the National Interconnected System (SIN) are regulated.

Law 1715 of May 2014 [6]; in this law some guidelines about generalities and definitions are given as follows: In title 1 called “Generalities”. And article 3 called “Definitions”. It is called a small-scale auto-generator (AGPE); to the system that has power less than or equal to 1 MW. Similarly, the distributed generator (GD) is referred to as the entity that generates electricity near the consumption canter’s, and is connected to the Local Distribution System and with installed power less than or equal to 0.1 MW. Article 3 mentions non-conventional sources of renewable energy and calls them (FNCER).

In this resolution it is specified in addition in title 2 called “integration to the network of self-generation and distributed generation”, and article 5 called “technical standards of system availability at voltage level 1”. That the sum of the installed power of the GD and AGPE must be equal to or less than 15 % of the nominal capacity of the circuit. In reference [6], the law 1715 of May 13, 2014 is decreed the law through which the integration of nonconventional renewable energies to the national energy system is regulated.

It is important to note that in Chapter 2, the provisions for the generation of electricity with non-conventional energy sources (FNCE) and the efficient management of energy are dictated. A call is made to Article 8, which specifies the promotion of self-generation to small, large-scale and distributed generation through excessive delivery mechanisms, bidirectional measurement systems, sale of energy by distributed generators, sale of credit energy, mass dissemination programs and targeted outreach programs.

It should be appreciated that the changes in the laws and energy regulations in Colombia are bringing about favourable change towards the initiatives of construction of photovoltaic solar systems disconnected from the network. It is interesting to note that at this time of regulatory changes in favor of non-conventional energies and in order to bring this technology to people and show how it works, the prototype construction of a solar photovoltaic system is presented. Which contemplates within its objectives, to establish a control of variable loads depending on relays of current, activated through programmed pulses with interface of communication between LabVIEW and Maker Hub library.

It is important to highlight that within the optimization of electrical systems, there is always the need to improve the parameters that affect the use of networks. These parameters affect the quality of energy in different scenarios. Such is the case of the scenarios that occur in photovoltaic electrical systems in terms of identification of sag, swell and detection of harmonics.
In this case of study, it is intended to show the analysis made to an electric signal of consumption in spaces from 0 to 1500 minutes. The processing of this signal will be done using the Discrete Wavelet Transform (DWT) and to dynamize this it will use the wavelet toolbox of MATLAB.

The following document will be presented as follows: As a first instance, an introduction will be presented, followed by a methodological stage with the design and calculation of all elements of the solar photovoltaic system at scale. Then we will present the design of the graphic control interface developed in LabVIEW software, presented the front panel and the block diagram. Following this, a description of the stage of physical construction with its parts will be presented.

To link the present work with the construction of the test prototype, an analysis of the discrete wavelet transform (DFT) will be presented, later a test case will be taken, the results will be analyzed and the conclusions will be stablished. Finally, acknowledgments and references will be presented.

2. Methodology design
In this section, the methodological design of this article will be presented.

2.1. Electric consumption
The first stage contemplated in the design of the solar photovoltaic system [7-10] to scale is framed in the dimensioning of the loads that will be part of the prototype. In the dimensioning, AC loads and DC loads were taken into account. For the purposes of designing and starting up the design of the prototype, low-wattage loads were taken into account. See Table 1. See Table 2.

| Table 1. Consumption in direct current. |
|----------------------------------------|
| **Consumption in direct current DC**    |
| Description | Number | P (W) | Hours / day | Days of use / week | Energy (Wh / week) |
| Fans        | 4      | 1.8   | 1           | 7                   | 50.4               |
| Total energy per day                     | 7.20 |
| Total energy DC                           | 50.4 |

2.2. Reference solar pico hours Formatting author names
Analyzing that, the solar system developed, takes as a base of location, the city of Cartagena in Colombia, it is noted that this city enjoys a high temperature during almost the twelve months of the year; with temperatures that vary from 30 to 40 degrees Celsius. and as it can be evidenced in the reference plane issued by the IDEAM, see Figure. 1, the radiation captured by cities in Colombia and in particular the solar irradiation of the city of Cartagena in the month of March, observing a variation in its space territorial between 4.5 and 6.5 Kwh / m. This data is important to be able to take the reference value of the peak solar hour HS [11]. With which the solar photovoltaic system was designed to scale.

Now taking into account the above and taking as reference the irradiation of the month of March. See Figure. 2, and applying a correction factor k = 0.95 and additionally mention that the photovoltaic solar panel is under a fixed structure and this has a slope of 45 degrees. Which would indicate that in this month we would be taking advantage of its maximum energy according to the inclination. It was estimated that in this period there is an abundance of solar irradiation and the sunset can vary between 6 and 9 hours. For purposes of validation of the design, the peak solar hours of 6.16 HSP.
Table 2. Consumption in alternate current AC.

| Description  | Number | P (W) | Hours / day | Days of use / week | Energy (Wh / week) |
|--------------|--------|-------|-------------|--------------------|--------------------|
| lights       | 4      | 0.7   | 1           | 7                  | 19.6               |
| Total energy per day |       |       |             |                    | 2.80               |
| Total energy AC   |       |       |             |                    | 19.6               |
| Total energy system week |       |       |             |                    | 70                 |
| Total energy system per day |       |       |             |                    | 10                 |

Figure 1. Radiation captured by cities in Colombia.

2.3. Global performance installation
For the calculation of the overall performance [12-14] of the installation. The individual yields of each one of the elements that are part of the solar photovoltaic system at scale were taken into account. The elements to take into account can be evidenced in Table 3. And the data sheet of the photovoltaic module to be used can be evidenced in Table 4.
Using “(1),” we calculate the overall performance of the installation. Taking into account the values in Table 3, it can be noted that the value of \( R = 0.6435 \) denotes an overall performance of the installation of 64.35%.

### Table 3. Elements and characteristics

| Description                                      | Parameter | Value |
|--------------------------------------------------|-----------|-------|
| New accumulations, without intense discharges    | \( K_b \) | 0.050 |
| Low self-discharge batteries                     | \( K_a \) | 0.002 |
| Inverter performance                             | \( K_c \) | 0.050 |
| Efficient charge controller                      | \( K_r \) | 0.100 |
| Losses in wiring and equipment                   | \( K_v \) | 0.150 |
| Battery discharged up to 60%                     | \( P_d \) | 0.600 |
| Number of days of autonomy to ensure a no-load service | \( N \) | 3     |

\[
R = \left(1 - K_b - K_c - K_r - K_v\right) \times \left(1 - K_a\right) \times \left(\frac{N}{P_d}\right)
\]

\[
R = 0.6435
\]

Where:

- \( K_b \): Coefficient of losses for performance in the accumulator.
- \( K_a \): Fraction of energy that is lost by self-discharge.
\( K_c \): Losses for the investor's performance.
\( K_i \): Losses in the charge controller
\( K_v \): Other losses not considered previously.
\( N \): Number of days of autonomy to ensure a no-load service.
\( P_d \): Maximum permissible discharge depth.

### 2.4. Solar panel calculation

In this stage of the design [15-17], the variables that we took into account and the calculation of the number of panels that are needed for the assembly of the solar photovoltaic system with an autonomy of three calendar days are presented. We needed to know the daily energy that the panels should provide, establishing a daily consumption and contrasting this with the overall performance of the installation. The daily energy that the panel was supposed to produce taking into account a selection was established.

Additionally, it was necessary to know, according to the selected panel. What was the energy produced by the system?

Using “(2),” we calculate the required energy that the panels have to supply.

Using “(3),” we calculate the energy produced per day by a photovoltaic panel.

\[
EDS = \frac{CD}{RG}
\]

\[
EDS = \frac{10}{0.6435}
\]

\[
EDS = 15.54(Wh/dia)
\]

\[
EDP = I_{pm} \times HSP
\]

\[
EDP = 0.56 \times 6.16
\]

\[
EDP = 3.45(Ah/paneldia)
\]

Where:

- \( CD \): Total consumption per day
- \( RG \): Global performance
- \( EDS \): Daily energy to be produced by solar panels
- \( EDP \): Energy produced per day by a photovoltaic panel
- \( HSP \): Peak Solar Hour

### Table 4. Data sheet of the photovoltaic module to be used

| Description | Unit | Value |
|-------------|------|-------|
| \( P_{max} \) | W    | 10    |
| \( V_{nom} \) | V    | 12    |
| \( V_{pm} \) | V    | 17.3  |
| \( I_{pm} \) | A    | 0.56  |
| \( V_{oc} \) | V    | 21.6  |
| \( I_{sc} \) | A    | 6.13  |
For the smart grid scale model after the enhanced calculations, it is concluded that: The number of panels needed is equal to one. Taking into account the considerations of connection forms this can be series or parallel. Using “(4),” we calculate the number of panels in series. Using “(5),” we calculate the number of panels in parallel.

\[ nps = \frac{V_s}{V_{nom}} = \frac{12}{12} = 1 \]  \hspace{1cm} (4)

\[ npp = \left( \frac{EDS}{I_{pm} \cdot HSP} \right) = \left( \frac{15.54}{\frac{12}{0.56 \cdot 6.16}} \right) = 0.37 \]  \hspace{1cm} (5)

Where:

- \( nps \): Number of panels in series
- \( npp \): Number of panels in parallel

For the construction of the solar photovoltaic system to scale, a solar panel of 10 Watts was taken into account and the current that it supplies is 0.56 Amperes (A).

2.5. Regulator sizing

In this stage of the design we took into account that the charge regulator should work at the same voltage of the system and in theory should be able to support a current intensity greater than the intensity of the solar panel for assembly in an approximate value of 10% [18-19].

Knowing that the panels provide a current intensity equal to 0.56 Amperes (A) and oversized this to 10%. It is obtained that the maximum intensity of the regulator is in the order of 0.62 Amperes (A). The regulator voltage is 12 volts (V).

2.6. Storage system calculation

At this stage of the design of the photovoltaic solar system, the storage system is presented [20-23]. At this point we had to calculate the capacity of the battery. For this purpose, we took into account data such as: Consumption, days of autonomy, voltage of the battery and depth of discharge of the battery selected for the assembly.

Knowing the Daily energy to be produced by solar panels (EDS), the days of autonomy (N), the nominal voltage (Vnom) of the battery equal to 12 volts and taking into account a discharge of 60% (Pd). Using “(6),” we calculate the accumulation capacity of the batteries in Ampere Hour (Ah).

In this stage of the design we took into account that the charge regulator should work at the same voltage of the system and in theory should be able to support a current intensity greater than the intensity of the solar panel for assembly in an approximate value of 10% [18-19].

\[ Abb = \left( \frac{EDS \cdot N}{V_{nom} \cdot \frac{P_d}{100}} \right) = 6(Ah) \]  \hspace{1cm} (6)

Where:
Abb: Accumulation capacity battery bank

For the development of the assembly of the equipment according to the calculations established, it is concluded that one battery is needed and this can be connected in series or parallel. For connection in specific connection was made in series.

Taking into account the previous considerations for the assembly of the battery in the scale system, the battery under reference FL1290 was taken into account with the characteristics shown in Table 5.

| Table 5. Specifications battery series FL1290 |
|---------------------------------------------|
| Description     | Unit | Value  |
| Cycle use       | V    | 14.6 – 14.8 |
| Standby use     | V    | 13.7 – 13.9 |
| Initial current | Less Than | 2.7 |
| \( V_{\text{nom}} \) | V    | 12    |
| Charge          | Ah   | 9.0   |

2.7. Inverter sizing

In the final stage of the design of the solar photovoltaic system at scale, the calculation of the Inverter [24-25] was presented and for this purpose the total power of the consumptions in alternating current was considered, estimated a total close to 2.8 watts. Now taking into account the consumption and voltage of the 12 volt system. Using (7), the minimum power of the inverter can be set to work efficiently.

\[
mpi = p_{ac} * 1.2
\]

\[
mpi = 2.8 * 1.2 .
\]

\[
mpi = 3.36(W)
\]  

Where:

\( mpi \): Minimum power of the inverter

To comply with the specifications of the design, when making the assembly of the solar photovoltaic system to scale. We took into account the inverter PI100LA. See Table 6.

| Table 6. Specifications inverter series PI100LA |
|-----------------------------------------------|
| Description          | Unit | Value       |
| Max. Power           | W    | 100         |
| High Surge Peak      | W    | 200         |
| Input Voltage        | V    | 12          |
| Output Voltage       | V    | 110         |
| Frequency            | Hz   | 60          |
| Fuse                | A    | 10          |
| Output Wave Form     |      | Modified Sine Wave |
| Power up To          | A    | 0.45        |
3. Control load system

Finished the dimensioning of the solar system to scale. We present the design of the graphic programming for the control of variable loads. To give emphasis to this process, the Block Diagram is presented, followed by the Front Panel developed in LabVIEW [26-31]. The communications and control interface for the sending and receiving of data was made through LabVIEW with Arduino and Maker Hub [30, 32-33].

3.1. Block diagram

Finished the dimensioning of the solar system to scale. We present the design of the graphic programming for the control of variable loads. To give emphasis to this process, the Block Diagram is presented, followed by the Front Panel.

In the development of the programming for the control of variable loads AC and DC, it is established as a starting point. Use graphic programming blocks embedded with Maker Hub library and LINX communications. To start the programming cycle, an open point and a close point are established. To establish iterative cycles within the programming for load control, it is established to use a while loop structure.

On the other hand, taking into account that the real system includes 4 AC loads and four DC loads. A matrix of 8 inputs and 8 outputs was created that were controlled by a Digital Write N Chanel. It is made clear that a serial port reading input is included in the input of the programming cycle, which will be monitoring the signal coming from the board. This reading input is normally works at 9600 bauds per second and the reading input will be made through the ports com and lpt of the laptop that will act as HMI screen. The graphic programming established through the Block Diagram of LabVIEW software is presented in Figure 3.

![Figure 3. Block Diagram load control system.](image)

3.2. Front panel

For the development of the control graphic environment, a man machine interface (HMI) was created in the LabVIEW programming software.
This environment allowed us to create a variable load control like the one observed in Figure 4. In this we can observe an embedded board named Arduino Mega 2560, a relay system for AC load control (lighting) and a relay system for control of DC loads (fans). The graphical control system of loads to relays of current accentuates its serial communication with the PC through the COM4 port. In the same way an emergency stop stage like STOP is created.

This graphic design looks like the frontal image of the prototype already built, see Figure 5.

4. Construction procedure
For the stage of physical construction of the prototype of solar photovoltaic system to scale, a rectangular container of 40 x 20 x 20 cm was built. On the upper base of the container, the 10-watt photovoltaic solar panel is supported at 45 degrees. On the front face of the model, is the control system. Where you can see the board, the AC loads (bulbs), the current relays, fuse protection system and wiring. On the left side face, there are DC loads (fans). On the back side is the regulator. Finally, in the internal part of the container, the connections with the battery and the inverter are immersed. See Figure 5a, 5b, 5c and 5d.
5. The wavelet transform

The wavelet transform (WT) is a mathematical processing technique commonly used in digital signal processing. This processing technique uses rectangular windows where the high and low frequencies are enclosed by applying them to scalar factors [34-36]. This method is mostly used for advanced frequency analysis over time. WT applications are included in ECG analysis, denoising signal, image filtering, image compression or as in this case is used for power quality analysis in electrical systems or electrical signals of voltage, current and power.

The wavelet transform can be found in the time domain. Wavelet Continuous Transform (CWT) and can be expressed mathematically using "8," of the following form.

\[
CWT_{\psi} f(a,b) = \int_{-\infty}^{+\infty} f(t)\psi_{a,b}(t)dt
\]

where

\[
\psi_{a,b}(t) = |a|^{-\frac{1}{2}} \psi\left( \frac{t-b}{a} \right)
\]  

(8)

On the other hand, the wavelet transform can be found in the frequency domain. Discrete Wavelet Transform (DWT) [37] and can be expressed using "9," in the following way.

\[
DWT_{\psi} f(m,n) = \int_{-\infty}^{+\infty} f(t)\psi_{m,n}(t)dt
\]

where

\[
\psi_{m,n}(t) = motherwavelet
\]  

(9)

Additional it must be mentioned that the DWT is used to design the multi resolution analysis (MRA). It should be clarified that the MRA represents the original signal in different resolutions after having applied two types of filters in each level. See Figure 6. Each of these called low pass filter (LPF) and high pass filter (HPF). It is specified that the MRA performed a scaling of the function \( \varnothing(t) \) using “10”.
Figure 6. Schematic Level multiresolution signal analysis of DWT

\[
\phi(t) = 2 \sum_{n=-\infty}^{\infty} c_n \phi(2t - n). \tag{10}
\]

\[
\psi(t) = 2 \sum_{n=-\infty}^{\infty} d_n \phi(2t - n). \tag{11}
\]

Where \(d_n\) is also a squared summable sequence.

6. Analysis result
To start the results stage, the signal to analyze is shown as the first instance. See Figure. 7. Then a call will be made from the MATLAB Wavelet toolbox [38] and their respective perturbations will be focused.

Figure 7. Analysis signal discrete wavelet transform
6.1. Sag detection

Figure 8. Wavelet db 4 at level 1

Figure 9. Wavelet db 8 at level 1
Taking into account the analysis made in level 1 with daubechies 4, 8 and 10 you can observe between the minutes 600 to 700 a behavior of sag voltage and likewise between the minutes 1100 to 1200. In each of these level daubechies One the behavior is similar. See Figure. 9, Figure. 10 and Figure. 10.

6.2. Harmonic detection
Taking into account the analysis done in level 4 with daubechies 4, a behavior similar to harmonics can be observed between 1300 and 1400 minutes. See Figure. 11.

When the daubechies [39] db 8 family is used, the behavior to analyze the signal reveals a greater number of harmonics in the original signal. these behaviors are detected between minutes 700 and 800. See Figure. 12.
When the daubechies db 10 family is used, the behavior to analyze the signal reveals the same behaviors that db 8 and the harmonic are detected between minutes 700 and 800, and 1100 and 1200. See Figure 13.

6.3. Swell detection
Taking into account the analysis done with the family db 8 in level 4, one can observe a swell behavior in d4 between the minutes 680 and 780, 850 and 900. Similarly, in db3 between minutes 760 and 840 but in a way a little less regular. See Figure 14.
7. Conclusions
In the present work the viability of using mathematical signal processing tools to analyze electrical signals is observed. This type of analysis is very helpful in the eventuality of wanting to implement filters that allow establishing or improving electrical signals due to signal fluctuations commonly experienced by medium and low voltage electrical distribution networks. The analysis through the wavelet transform and the wavelet mother through level daubechies allowed establishing that these small signals can be located. Future work is expected to establish digital filters that can suppress these small variations that affect electrical signals.

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