Noname manuscript No.
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Oscillation analysis of Low-Voltage distribution systems with high penetration of photovoltaic generation

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Received: date / Accepted: date

Abstract The use of Renewable Power Generation brings new challenges related to power quality issues. Furthermore, with the changing power system nature due to the presence of new components such as power electronics in large numbers and distributed generation systems, the tools used for more than a century to analyze signals in this type of systems are no longer providing accurate information with a good resolution in time and frequency domain. To contribute with a new view of the problem, this paper presents a hybrid technique for the analysis of oscillations in Low Voltage distribution systems considering photovoltaic generation. The aim is to characterize the behavior of the system in a time-frequency domain and get the different instantaneous frequencies that appear. The results obtained with this technique are compared with three well-known methods of analysis. The validation of the methodology is carried out in a real-time digital simulator of a distributed system with Photovoltaic generation.

Keywords Solar Generation · Hilbert Huang Transform · Fourier Transform · Wavelet Transform · Oscillations Analysis

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1 Introduction

The notion of Instantaneous Frequency (IF) has not been previously explored in power systems but with the arrival of new technologies such as distributed generation, nonlinear loads and electronic devices was necessary to include that concept [22]. For many years, different methods have been used for the analysis of signals in power systems. Fourier analysis is one of the methods with more applications reported [15], [30] but it has some restriction with the time-frequency resolution.
Some of the most common strategies used in power systems for signal analysis are the Fast Fourier Transform (FFT), the Short Time Fourier Transform (STFT), the Wavelet Transform (WT) and Wigner-Ville Transform (WVT); all of them with their inherent limitation of time or frequency resolutions [4], [40]. The Hilbert-Huang Transform (HHT) has emerged as an alternative to support the analysis of nonlinear and nonstationary multi-component signals in power systems [18].
In modern power systems is necessary to analyze complex oscillatory processes, harmonics, nonlinear and non-stationary signals and the conventional methods have problems but the HHT can deal with this kind of signals. WT is a powerful signal-processing tool that is particularly useful for the analysis of non-stationary signals [5], and WVT has a better resolution than SFFT [40]. These techniques have been used independently and sometimes in combination to obtain a better performance, therefore in this paper, a hybrid technique that combines different methods of analysis is proposed.

The acquisition and monitoring process is increasingly complex due to the massive use of non-linear loads and electronic-based equipment in residential, commercial, and industrial plants [3]. It is very important to implement and develop on-line and off-line systems that can check the power fluctuations, related to the power absorbed by the numerous loads of each user [28], [21]. The complexity depends on the characteristics of the electrical signals of the modern equipment, which are related to the different loads (static, rotating and power electronics-based) and generators (deterministic-based, stochastic-based) [34].

In distribution systems, the most important challenges are related to voltage rise and overloading of system components. The integration of many Photovoltaics (PV) generators in an existing grid produces a significant rise in the local voltage levels due to reverse power flow [13]. The active power generation has a linear relation with the solar isolation, however, the network behavior is affected by events that produce nonlinear phenomena, for example, a PV inverter with lower switching frequency can generate high harmonic distortion. Therefore, the signal analysis in these systems is fundamental to characterize harmonics or detect frequencies at different operating conditions. The analysis of complicated system oscillations using a time-frequency behaviour provide useful information on the slow and fast evolution of system dynamics.

In this paper, an oscillation analysis is performed by using reactive power data for one Low Voltage (LV) distribution system with PV generation. We explore the use of the Hybrid Technique which is mainly composed of WT, FFT, and HHT for instantaneous frequency detection, in the search for a new application of this adaptive algorithm that can be used to analyze signals from these domains without the need to make many a-priory adjustments. The frequencies calculated via the Hybrid Technique are compared to those obtained using conventional methods, showing a wider spectrum of significant modes mainly due to the non-periodical behavior of the power signals. The main motivation is to show which of the comparative strategies has better performance in LV distribution systems.

This paper is organized as follows: Section 2 describes the recent trends in Power Quality in distribution systems considering distributed generation. Section 3 presents a Review of Hilbert Huang Transforms and its applications in power systems. The system used to validate the methodology is presented in Section 4. Finally, the results and conclusions are shown in Section 5 and 6 respectively.

2 Oscillations in distribution systems considering distributed generation

High PV penetration in LV distribution systems produces certain technical effects because the network design initially does not consider their integration. Active power fluctuations result in severe frequency variations in the electrical network (this is only true if X/R ratio is very large, which is not true anymore in distribution systems) [8]. In this particular case, voltage flickers occur more frequently at higher penetration of PV systems during clouds transients [13], as well as, it may cause problem switching of capacitor banks due to reactive power variations [20]. The main strategies to control PV systems can be classified as Local control Schemes, Decentralized Control Schemes and Central control Schemes [8], [7].
Local control schemes (also known as droop-based regulation strategies) make autonomous control of the reactive power supply via characteristic curves. For example in Germany, the local voltage-control strategies proposed by the code of practice VDE-A-N 4105 are: Fixed $\cos\varphi$, Power factor characteristic ($\cos\varphi(P)$ method) and Reactive power/voltage characteristic ($Q(U)$ method)[26]. The fixed $\cos\varphi$ method relates the production of the reactive power proportionally to the active power production, and it is inherently enabled as long as the irradiance level(2). Consequently, during the low active power generation, the absorbed reactive power will also be as low as the active power by keeping the proportionality C_1, as follows:

$$\begin{aligned} \cos\varphi &= constant \text{ , } Q{=}\tan(\arccos\varphi)P \\ Q &= PC_1 \end{aligned} \tag{1}$$

$$\begin{array}{c} \cos\varphi_1,\ P \leqslant P_1 \\ \cos\varphi_1 + (1-\cos\varphi_1)\frac{P_1-P}{P_1-P_2,}\ P_1 < P \leqslant P_2 \\ -1 + (1-\cos\varphi_2)\frac{P_2-P}{P_2-P_3,}\ P_2 < P \leqslant P_3 \\ \cos\varphi_2,\ P > P_3 \end{array}. \tag{2}$$

On the other hand, in the $Q(U)$ method the reactive power of the inverter is regulated as a function of the voltage at the coupling point. It is worth noting that two droop ratios are available when the voltage is higher than the normal range. Besides, achieving better voltage control functions can differentiate the voltage responses of the inverters near LV transformer from the rest along the feeder, so the reactive power contributions from all inverters along the feeder can be more equally distributed as in the case of the $\cos\varphi(P)$ method [2]. As stated in the German Code (GC), the droop curve for the $Q(U)$ method is provided by the network operator.
The calculation of the reference reactive power in the $Q(U)$ can be summarized by (3).

$$\begin{array}{c} Q_{max},\ U < U_{min} \\ \frac{U-U_1}{U_{min}-U_1} \cdot Q_{max},\ U_{min} \leqslant U < U_1 \\ 0,\ U_1 \leqslant U \leqslant U_2 \\ -\frac{U-U_2}{U_{max}-U_2} \cdot Q_{max},\ U_2 < U \leqslant U_{max} \\ -Q_{max},\ U > U_{max} \end{array}. \tag{3}$$

The technical effectiveness of these voltage-control strategies has been studied [16], [9], [12], [39]. Moreover, non-deterministic techniques have been implemented to control the reactive power of smart PV inverters. Systems with conventional fuzzy controllers present good performance characteristics, as the authors have shown in previous works [8], [7].

Reduce oscillations of the reactive power is vital and necessary for future well-managed penetration of PVs via control strategies. One solution could be the design of active/passive filters. However, when a filter is used to decrease the reactive power fluctuations generated by a reactive power control method, the voltage boundary may be overpassed [6]. One of the major problems that appear in these types of analysis is the shape of the signals that are obtained. These signals are not pure sinusoidal with some already known harmonic components to be filtered, they include solar irradiance transients [2], [33]. Solar irradiance transients are produced by over-passing clouds that generate shadow. The impact of cloud induced solar transients that affect each solar PV unit differently within a distribution network cannot be accurately studied [1]. This is an important factor when the design wants to mitigate undesired fluctuations in real-time, without affecting the proper action of the controller. This is the reason why the HHT and Hybrid Technique has become an alternative solution to the problem of obtaining information from the signals acquired by the smart meters. Some previous works have used HHT for power quality analysis [32], [42], [38], [25] but they did not consider signals coming from systems with PV generation.

3 A review of Hilbert Huang Transform

The HHT was created initially to study ocean waves, which are non-stationary and nonlinear but over time its application has been spread to other fields. The HHT is constituted by the empirical mode decomposition (EMD) and the Hilbert spectral (HS) analysis [19].

3.1 Empirical Mode Decomposition

The Empirical Mode Decomposition method aims to decompose the nonlinear and non-stationary signal $x(t)$ into a finite sum of independent modes called intrinsic Mode Functions (IMFs). The IMFs are obtained from the original signal and satisfies two conditions [43]:

1. The number of extrema and the number of zero crossings must be the same or differ at most by one.
2. At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

The EMD algorithm for the signal $x(t)$ can be summarized as follows [19], [24]:

Algorithm 1 The empirical mode decomposition

1. Identify all extrema (maxima and minima) in $x(t)$.
2. Compute an upper $e_u(t)$ and a lower $e_l(t)$ envelope by interpolation (cubic splines)
3. Determine the local mean as $m(t) = (e_u(t) + e_m(l))/2$.
4. Obtain the residue $r(t) = x(t) - m(t)$
5. Iterate until the number of extrema = number of zero-crossing ± 1
6. subtract the so-obtained Intrinsic Mode Function (IMF) from the original signal
7. Iterate on the residual until $r(t)$ it becomes monotonic.

The main goal of the application of HHT is to have a tool to manage the time-frequency-energy paradigm of data. One way to express the non-stationarity is to find instantaneous frequency and instantaneous amplitude. This was the reason why Hilbert Spectrum (HS) analysis was included as a part of HHT. Spectral analysis is a powerful tool to analyze the statistical characteristics of stochastic data [11]. A HS is a 3D representation of the instantaneous amplitude and frequency as a function of time for each Intrinsic Mode Function.

The HS is defined as:

$$H_i(f,t) \triangleq \begin{cases} a_i(t) & \text{for } f = f_i(t) \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

For a general multicomponent signal, the Hilbert Spectrum is defined as the sum of Hilbert Spectra of all the IMFs, as given in:

$$H(f,t) \triangleq \sum_{i=1}^{N} H_i(f,t), \tag{5}$$

where N is the total number of IMFs.

3.2 Instantaneous Frequency detection

The notion of IF has been previously explored in [28] and [27]; because in practice, signals are not truly sinusoidal and the concept of frequency must be analyzed in greater depth. Some research has been done on this subject, however, many aspects remain open for discussion. Generally, signals coming from the physical world have been analyzed using the Fourier transform, which gives time-invariant amplitude and frequency values. The inherited uncertainty principle associated with the Fourier transform makes the concept of an Instantaneous Frequency hard to define because the uncertainty principle is a consequence of the Fourier transform (or any other type of integral transform). Thus, if they are not applying an integral transform in the frequency computation, we would not be bounded by the uncertainty principle [43]. From a Fourier analysis point of view, the frequency of a signal would be derived from its time period, which is the time taken to complete one stationary time period. However, for a non-stationary waveform, the frequency would be hard to define. Another way to define the frequency is as the angular velocity that corresponds with the rate of change of its phase. If it is possible to define a unique phase for a signal, it will be possible to calculate its rate of change and thereby its frequency. The frequency obtained in this way is unique at any instant in time and is called instantaneous frequency. It is possible to define only one instantaneous frequency for a signal at any point in time [28], [27]. This method has a problem to multi-component signals and therefore requires a pre- decomposition, where EMD can be called upon.
Historically, IF was computed from analytic signals (AS) through the Hilbert transform. The HT, however, deals poorly with multi-component signals. HHT estimates the instantaneous frequency and amplitude of a given signal and to do this, it first decomposes any signal down to mono-components called intrinsic mode function (IMF) by using the Empirical mode decomposition (EMD). With the function $x(t)$ defined as

$$x(t) = r(t) + \sum c_i(t) = r(t) + \sum a_i(t)\cos(\theta_i(t)), \tag{6}$$

where $c_i(t)$ is the IMF number i, $a_i(t)$ and $(\theta_i(t))$ are $c_i(t)'s$ instantaneous amplitude and phase respectively. The residual $r(t)$ is a monotone function. The instantaneous frequency $f_i(t)$ for each IMF $c_i(t)$ is defined by

$$f_i(t) \triangleq \frac{1}{2\pi} \cdot \frac{d\theta_i(t)}{dt}. \tag{7}$$

3.3 Hilbert-Huang Transform in Power Systems

The electrical signals observed in the modern power systems can be linear and nonlinear, stationary and non-stationary, periodic and non-periodic and this is due to the variability of the sources of generation (for example wind and solar energy) and the massive use of nonlinear loads and electronic devices connected [42]. In [32], it is possible to see one application to analyze active and reactive power absorbed by different types of loads with conventional generation using FT, WT, and HHT. The paper shows that the HHT allows an extraction of the characteristic properties of the electrical signals, which are not identifiable using FFT and WT. In [27] various refinement of the EMD algorithm and a local Hilbert Transform have been presented and applied for extracting and characterizing temporal behavior in power systems. Especially in low frequencies, the algorithm has a good performance. Something similar is shown in [24] where the authors perform a frequency analysis in electric interconnected systems.

In [23] a non-stationary data-based refined approach for characterizing temporal behavior based on the HHT has been proposed. The method allows automated extraction and characterization of temporal modal behavior with no prior assumptions on the governing processes driving the oscillations and can be applied to a wide variety of signals found in power system oscillatory processes.

One application of non-stationary time-frequency analysis techniques to identify nonlinear trends and filtering frequency components of the dynamics of large, interconnected power systems is presented in [28]. Finally, in [31] the mode mixing problem is analyzed in power systems; the authors present an improved masking signal approach.

Recently, some papers have shown the stability analysis in power systems under increasing penetration of photovoltaic power plants [13], [35], [37]; however, the oscillations analysis in this type of systems has not been addressed and the use of HHT appears as an alternative solution to this problem.

4 Implementation of the proposed scheme using Real-time digital simulator

A hardware-in-the-loop real-time simulator is constructed by using the xPC target toolbox of MATLAB. The xPC toolbox may convert the simulation model constructed in Matlab/Simulink SimPowerSystems into xPC real-time kernel code through real-time workshop, and then download the real-time kernel code into the xPC target machine. There are three major components to any xPC system: The host machine, the xPC target machine, and the plant. The host PC can be any PC running MATLAB/ Simulink, the Real-Time Workshop and xPC Target toolboxes. The xPC operating principle is shown in Fig.1, and the Real time simulator used for the test is shown in Fig.2

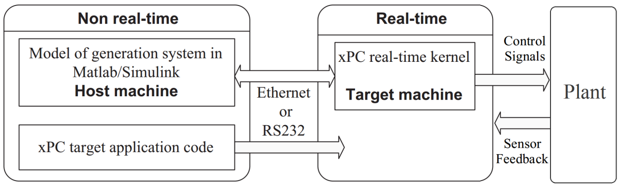

Fig. 1 XPC operating principle.

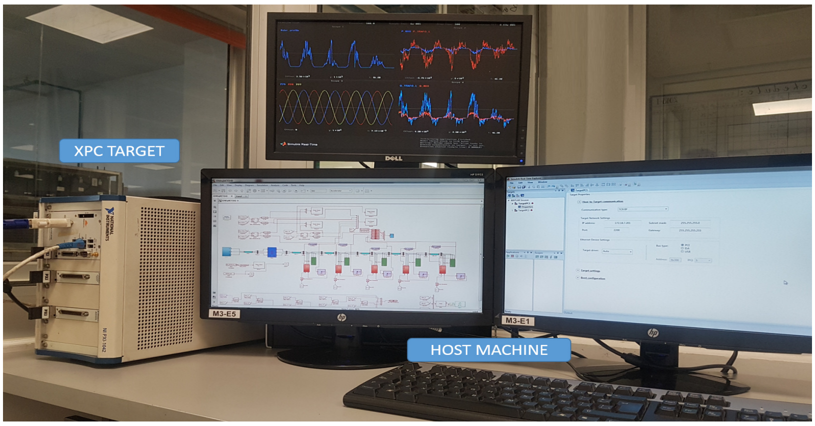

Fig. 2 Experimental set-up for the evaluation of the proposed strategy

To face the new constraints of LV distribution systems with high penetration of PV generation, distribution networks need to consider those components that were not included in the typical modeling and analysis of power distribution systems [3], [39]. It is for this reason that a schematic diagram representing a German LV distribution system was created in the host PC, including different components as smart homes, smart meters, and smart PV inverters. In order to do that, certain Simulink blocks were inserted into the diagram, some from the SimPowerSystem toolbox and others self-created to run in real-time applications representing different I/O hardware in the xPC target machine from the xPC Target toolbox.

One disadvantage in LV distribution systems modeling is that households are assumed as constant power loads, focusing more on the modeling of the generation units instead of the load design [12], [41]. In contrast, in this paper, the loads correspond to smart homes, which inject or absorb active and reactive power from the grid, as a part of a smart LV distribution system. In this way, the modeled smart LV distribution system is composed of 5 smart homes equipped with a scalable PV system and their respective smart PV inverters for reactive power control support. For the application used in this paper, the $Q(U)$ method is implemented in all the smart PV inverters. The solar installations are defined at a maximum $5.5kVA$ including a 10% overrating to support a reactive power compensation up to 46%, even when smart PV inverters operate with full power generation. The smart homes have a three-phase connection with a nominal line-to-neutral voltage of $230V$ and feeder cables type $NYY4X25mm2$.

The simulation is based on the reported daily solar radiation for the fall season of 2012 in the south of Germany, where some days have high solar radiation, and others have poor solar radiation. The resulting daily demand profile for the five smart homes is based on the methodology proposed in [10]. The resulting data are stored in the target machine and exchanged after simulation ends for its analysis, as presented in the following section.

5 Results and discussion

When using different methods for signal analysis, it is possible to use an index that allows comparing the performance of each method. Recently in [14], [29] they have used entropy analysis and similarity index. In the case presented in this paper, the objective is to make a comparison based on the possibility of distinguishing the different frequencies that appear due to disturbances, and that is the approach that the analysis will take.
The main objective of this paper is to identify the different frequencies that appear in the acquired signals and recognize patterns of behavior. In Fig. 3 the structure of the smart LV distribution system used for the validation is shown. It has been used the signals obtained in the points $M1$, $M2$ and $M3$. In $M1$ it is possible to observe the active and reactive power measured in the primary winding of the transformer. In $M2$ the active and reactive power of house 1 is measured, and in $M3$ appears the same measurements but in house 5. These measurements allow us to analyze the system in different cases.

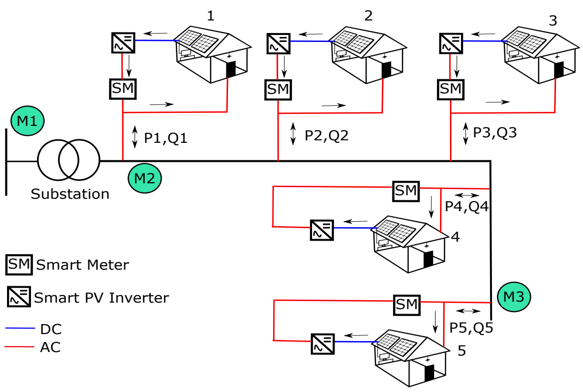

Fig. 3 Low Voltage Distribution System

In Fig. 4, it is possible to see all the measurements taken according to the description in Fig. 3. The sample time of the real-time simulation was $Ts = 60\mu s$, with an average task execution time (TET) of $Ts = 19.1\mu s$. The instantaneous values of active and reactive power in the primary winding in the transformer for 480s of simulation representing 5 different power profiles are shown in Fig.4a and 4d.

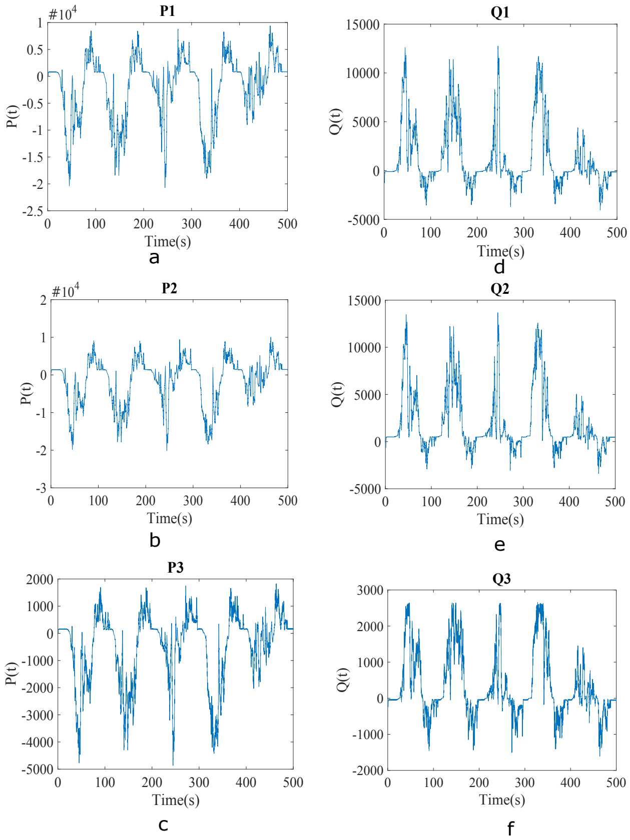

Fig. 4 Power signals measured at different points of the distribution system. a) Active Power in Watts (W) in M1, b) Active Power in Watts (W) in M2, c) Active Power in Watts (W) in M3, d) Reactive Power in volt-ampere reactive (VAR) in M1, e) Reactive Power in volt-ampere reactive (VAR) in M2, f) Reactive Power in volt-ampere reactive (VAR) in M3

The active and reactive power in the first house are shown in Fig.4b and 4e, and finally the active and reactive power in the last house in the grid are shown in Fig.4c and 4f respectively. It is clear that the injection-absorption of reactive power into-from the grid in $M3$ is lowest because it is required to maintain the voltage at the appropriate levels of operation and the distance from the transformer is greater. It is possible to see harmonics in the acquired signals due to the model used for smart houses which considers the real behavior of residential users. In particular, high reactive power fluctuations are observed by the use of the $Q(U)$ method. As the reactive power depends on the voltage magnitude measured at the respective coupling point, the reactive power changes proportionally to the PV active power injection or absorption. These fluctuations in LV distribution systems may negatively impact the power quality of the electrical network in a variety of ways.

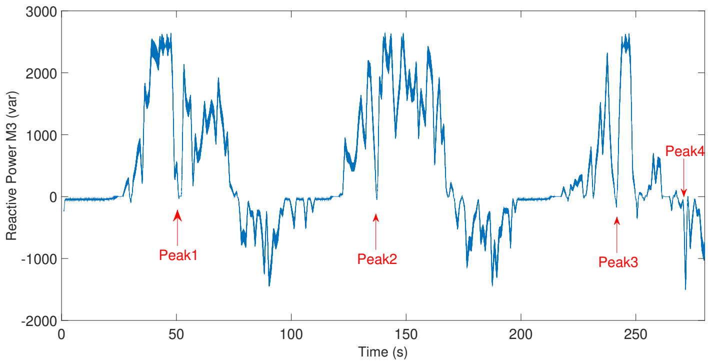

Fig. 5 Description of reactive power behavior of smart homes

In Fig.5, the reactive power fluctuation, due to the smart home closer to the end of the line, is represented. The resulting reactive power has maximum peaks around 2.8kvar, showing the limit of the smart PV inverter loading. Critical peaks of reactive power are represented in points 1-4. As can be seen, the reactive power output can variate from 2.2 kvar to zero and again to 2.8 kvar in an instant for peaks 2 and 3, this occurs because of the presence of a cloud and the injection of active power into the grid is reduced momentarily to zero generating a high reactive power fluctuation. Another critical reactive power fluctuation is represented in peak 4, as the smart PV inverter reacts injecting reactive power to raise the voltage at night when smart appliances are turned on. In general, both instantaneous fluctuations in reactive power (from injecting to zero or from absorbing to zero) are not desired, because reactive power production can limit a generator real power capability. If this increases too much, transmission lines may go offline, overloading other lines and potentially causing cascading failures.

5.1 Fast Fourier Transform (FFT)

The Fourier spectrum for the active and reactive power at each measuring point is shown in the Fig.6. In Fig.6, it is possible to identify two frequency components in all the measurements; the first component appears in 0.4 x $10^{-6} Hz$ and the second in 0.76 x $10^{-6} Hz$. In the spectrogram, it is possible to see more frequency components, but it is difficult to identify with accuracy each of these frequencies, as the frequency resolution is weak. Another important characteristic of the signal analyzed is the noise and the disturbances that appear. Usually, this is represented with low-frequency components that are difficult to detect using FFT. In the event of non-stationary components, FFT results are non-informative or provides little information at best.

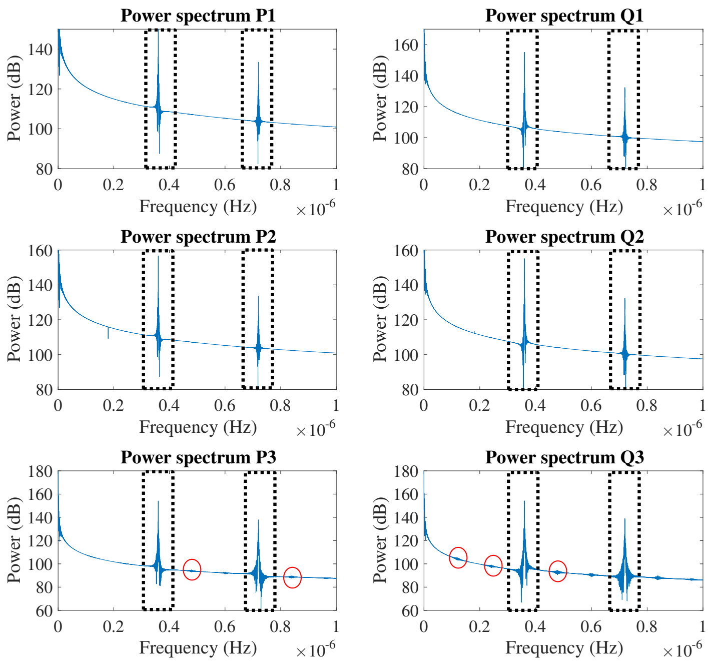

Fig. 6 Fourier Analysis

5.2 Wavelet Transform

The WT analysis is an effective mathematical method for studying the non-stationary behavior of electrical signals. The Discrete Wavelet Transform (DWT) of a signal $x(t)$ is calculated by passing it through a series of filters. The result of wavelet decomposition is hierarchically organized and it is possible to select the decomposition level based on a desired cutoff frequency. In WT exists a trade-off between the order of the wavelet function and the computation time. Higher-order wavelets are better able to distinguish between the various frequencies but require more computation time. The Wavelet Decomposition for the reactive power in the house 5 is shown in the Fig. 7. In this case, we select 20 levels of decomposition. A new representation is obtained for the original signal and it is composed by approximation (a20 in Fig.7) and details (d1 to d20 in Fig. 7).

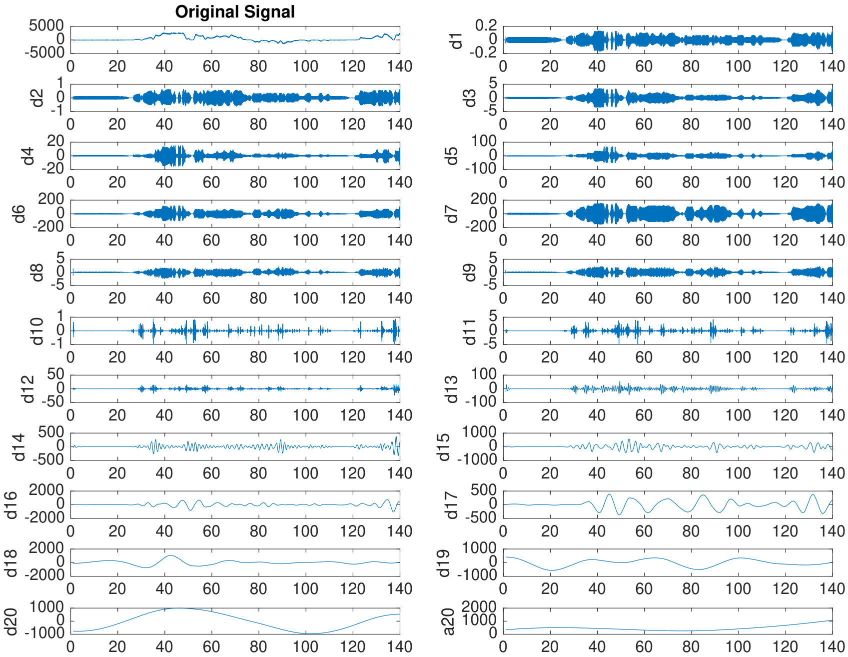

Fig. 7 Wavelet Decomposition

It is possible to see one frequency component between the sample 0.5x10^6 and 1.5x10^6, then the component disappears and can be observed again between the sample 2x10^6 and 2.5x10^6. The frequency component appears when the original signal has greater oscillations but between the sample 1.5x10^6 and 2x10^6, when the magnitude of the signal is lower, the oscillation frequency is not detected.

The WT has big problems related with the computational time when is used in large volumes of data as in this paper.

5.3 Hilbert Huang Transform

It is noted that, among other types of methods, EMD allows removing noise at all frequencies since these components are concentrated in some IMFs.
One of the main problems that appears with EMD is the phenomenon called mode mixing. The mode mixing problem is related to the presence of different frequencies (oscillations) in the same IMF. For example, in Figure 8 this phenomenon is very clear. In a previous work, the authors have established a way to solve this problem [17].

In Fig. 8, it is possible to see the last 5 IMFs and the residue obtained for the reactive power in house 1. In front of each IMF appears its corresponding instantaneous frequency. It can be observed that the number of oscillations decreases until the residue is reached, and this is reflected in the same way in the instantaneous frequency. The criterion for selecting the IMFs is its amplitude. In the IMF 14 that appears in Fig.8, it is possible to see a periodic behavior and therefore its Instantaneous frequency tends to a constant value. In IF residue a peak around $100s$ is observed, this event is also observed in IF11 and IF12. In the HS obtained for the IMFs selected shown in Fig.9, it is possible to see in HS residue a clear oscillatory behavior. In HS 10 and HS 11, the oscillations are stronger in a certain range of time.
In the Fig. 10 appears the reconstructed signal using only these IMFs and the residue shown in Fig.8. This is an example of how the application of HHT can improve the performance of the power system.Clearly the trajectory is now smoother and some of the unwanted peaks have been eliminated but the magnitude of the reactive power applied is the same. The reconstructed reactive power can replace the original signal and apply directly to the grid allowing better system behavior with fewer oscillations. This strategy can be combined with the reactive power control systems, which usually have as output the injected power to the converters.

The advantages of the reconstruction effect can be seen in the period of time between 80 seconds and 100 seconds, where the trajectory of the reactive power now has a much better behavior for the distribution system.

5.4 Hybrid Technique

A hybrid technique that consists in the combination of traditional analysis methods to establish a new strategy with greater efficiency is presented [36], and one of the main advantages is the extraction of characteristics in a lower computational effort. In this case, the combination is performed as follows: Hilbert Huang Transform+Wavelet Transform (HHT+WT), Hilbert Huang Transform+Fast Fourier Transform (HHT+FFT) and Hilbert Huang Transform+Wavelet Transform+Fast Fourier Transform (HHT+WT+FFT). These strategies will be performed for the reactive power at point M1, shown in Fig.4d.

5.4.1 HHT+WT

When performing the WT, filtering is applied to the signal, facilitating the separation of modes as shown in Fig. 11. By comparing this methodology with that obtained from HHT, it clearly shows a 60% reduction in the amount of IMFs developed and a 68% reduction when confronted with the WT. The reactive power signal at point M1 is broken down into 8 IMFs, as shown in Fig. 11 and its corresponding Instantaneous Frequency (IF) in Fig. 12. The

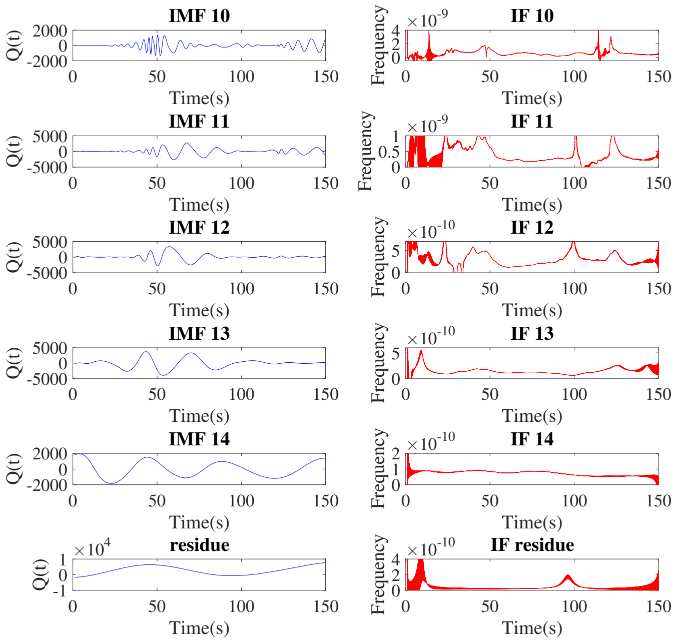

Fig. 8 IMFs an IF for reactive power in house 1

result is governed by what is obtained in the application of HHT, the greater the number of IMFs the signal oscillations is decreased. The first three IMFs extract the noise-contaminated characteristics provided by the nature of the inverter. IMFs 4 and 6 are not relevant for the analysis of the behavior of the system's reactive power, on the contrary, IMFs 6, 7 and 8 represent the power fluctuations of the PV system. But everything is not good, the result shows us a mixture of modes in Fig. 12 which makes it impossible to detect the frequency of oscillation of the reactive power.

5.4.2 HHT+FFT

Looking to find an efficient technique for frequency separation, avoiding what is shown in Fig. 6 and Fig. 7, the combination of FFT and HHT is proposed.

Similar to the result obtained with the HHT+FFT technique, the number of IMFs is reduced by 60% in the amount of IMFs developed and a 68% reduction when confronted with the FFT. But unlike the HHT+WT technique, in this case, greater accuracy is shown in the decomposition of the characteristic frequencies of the system. In this case, the first two IMFs represent noise pollution, in small power fluctuations due to the PV system inverter. Especially, it is shown in IMF 1, where these variations of the reactive power are precisely

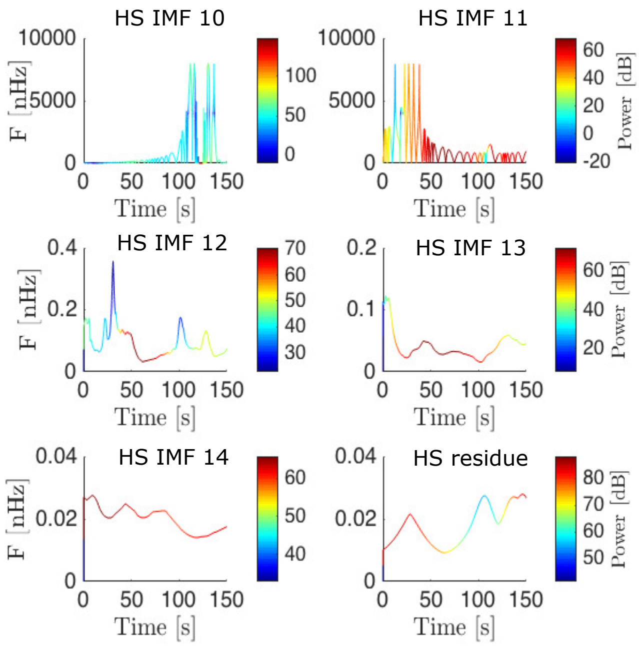

Fig. 9 Hilbert Spectrum for reactive power in house 1

separated due to inverter switching. The other IMFs represent very well the behavior of the PV system, facilitating the understanding of the fluctuations of the reactive power on such systems in Fig. 13. Also, the problem of mixing modes is reduced by a large percentage compared to the methodology shown above, as shown in Fig 14. Frequency components of $0.2Hz$ and $0.1Hz$ are evident in IMFs 4 and 5, respectively.

5.4.3 HHT+WT+FFT

This strategy brings the best qualities of HHT, WT, and FFT, establishing an efficient signal analysis tool, breaking the paradigm of amplitude-time-frequency analysis. The results show a 65% reduction in the number of IMFs compared to HHT and a 72% reduction from WT. Also, for HHT+WT and HHT+FFT strategies, there is a 12.5% reduction in the amount of IMFs. This efficiency is not only in the number of IMFs but in the accuracy with which the strategy separates the characteristic oscillations of the system.

When the HHT is applied to the last signal in Fig. 15, we get the IMFs and IFs shown in Figures 16 and 17, respectively. The first two IMFs contain noise signals that are not relevant for the analysis. On the contrary, other IMFs are of great importance for the understanding of the PV system. In particular, IMFs 4 and 5 show the same phenomena as the original signal, but at a smaller

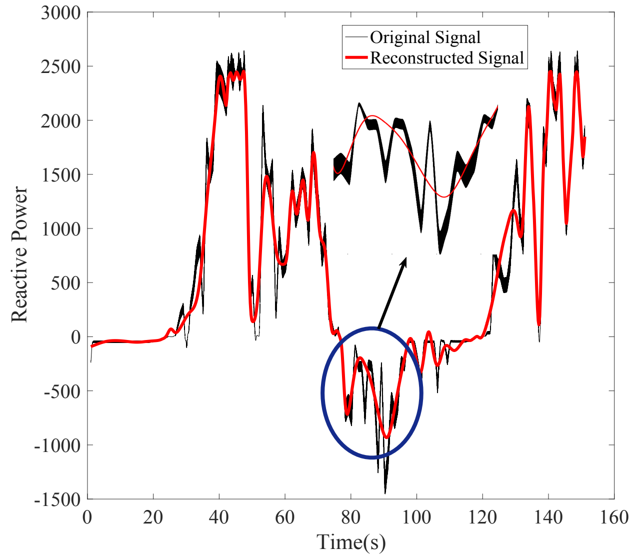

Fig. 10 Reconstructed signal for reactive power in House 1

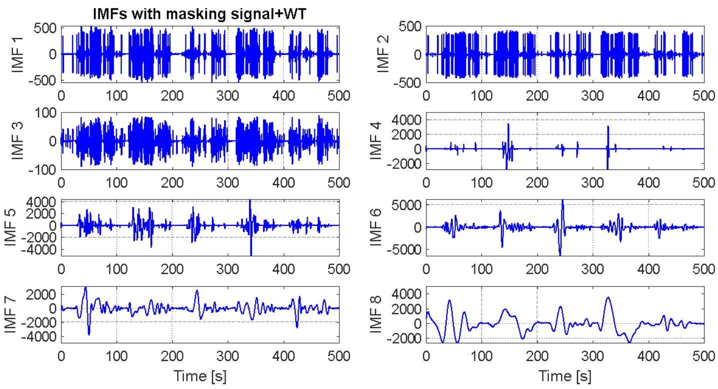

Fig. 11 Decomposition using EMD with HHT+WT.

magnitude, that makes it easier to see the oscillations and fluctuations in the PV system. In Fig. 17, it can be seen that IMFs 1, 2 and 3 present a large issue of mode mixing, in IMF 4, it is presented partially and IMF 5, 6 and 7 this mode mixing issue is not present, thanks to the ability of this method to be able to separate the noise from the characteristic signals precisely.

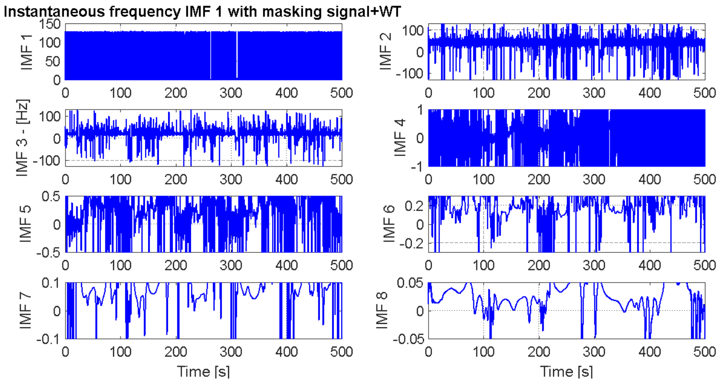

Fig. 12 Instantaneous frequency using EMD with HHT+WT.

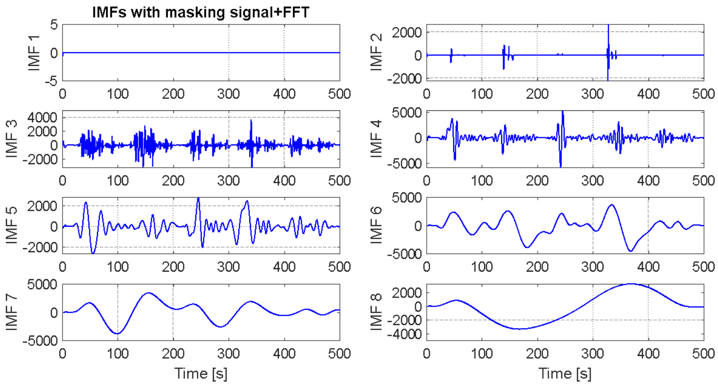

Fig. 13 Decomposition using EMD with HHT+FFT.

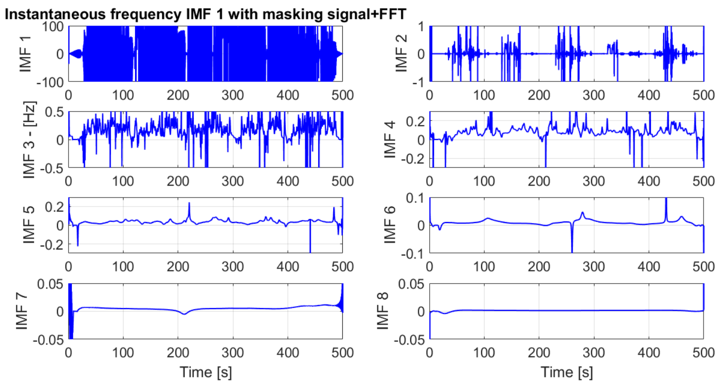

Fig. 14 Instantaneous frequency using EMD with HHT+FFT.

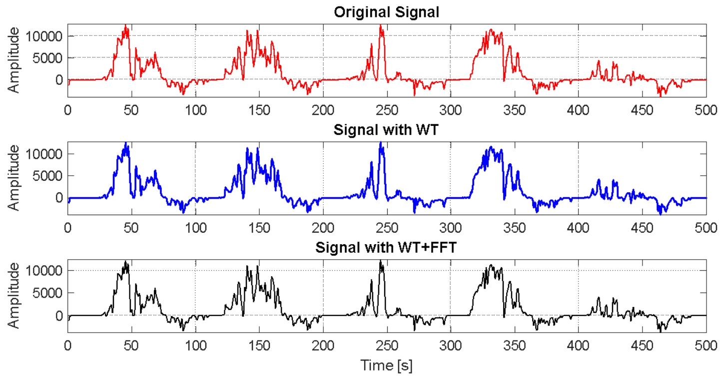

Fig. 15 Reactive power in M1, signal after applying WT, finally the signal with WT+FFT

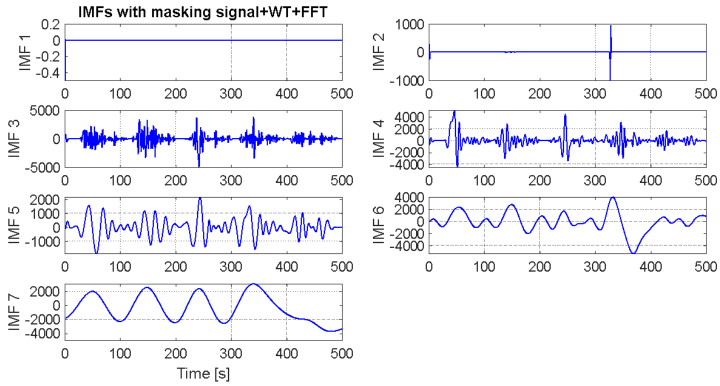

Fig. 16 Decomposition using EMD with HHT+WT+FFT.

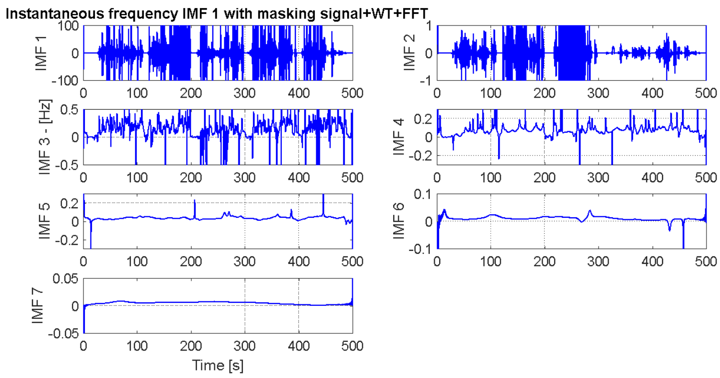

Fig. 17 Instantaneous frequency using EMD with HHT+WT+FFT

6 Conclusions

Three different methods to analyze modern power systems characterized by oscillatory behavior are studied in this paper. The oscillations are produced as

a result of the stochastic nature of primary resource (sun), the load variation and the fluctuations in the inverter and controllers. Through this study, it has become clear that Spectral analysis of power system oscillatory signal data is a challenging task. The analysis of oscillations and the signal reconstruction from the IMFs helps to provide a well-behaved reactive power profile that can be further used in the inverter controllers. From the smoothed Q profiles observed, this technique can be an alternative for the management of information delivered by the sensors available in the distribution networks. Such information can be further used to plan control actions, fault location, the elimination of noise components and any type of analysis that requires the use of big data. The HHT has better computing efficiency than WT, which means that the HHT is more suitable for large size signal analysis. The hybrid method is much better than WT and HHT, this method can break down the signal into fewer IMFs than traditional strategies.
A good selection of IMFs allows to have a new signal without noise and with the main frequency components. This could be applied to smooth the reactive power fluctuations of the PV inverters in conventional voltage-control strategies. In some cases, it will be necessary to establish classification thresholds to select the IMFs using parameters such as energy, standard deviation or entropy, in our case we have obtained a reasonably good result considering only the amplitudes of the IMFs. Finally, the use if the real-time digital simulator allows us to ensure that the results obtained can be adapted in real systems.

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