Chaotic Characterization of Solar Cell Open Circuit Voltage

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Abstract:

The fluctuations accompanying the DC offset in a photovoltaic cell open circuit voltage waveform are studied. Nonlinear analyses performed on these waveforms ascertain the presence of a highly unstable chaotic behavior. The results are validated using various parameters such as Kolmogorov Entropy, Fractal Dimension and Lyapunov Exponent. It is observed that the chaotic behavior responds to atmospheric and cosmic disturbances and hence can be used to study such effects. The information and inferences about the chaotic behavior coupled with proper synchronization techniques could potentially lead to cost effective means of enhancing the solar cell output.

Keywords: Photovoltaic Cell, Chaotic Characterization, Open Circuit Voltage

1. Introduction:

In the present era of renewable energy technology, the harnessing of solar energy using photovoltaic cells stands out as the frontrunner[1,2,3]. While on one hand, the research on improving photovoltaic efficiency by means of using new materials with state-of-the-art fabrication techniques continues unabated, the complexities involved in the fabrication of such materials as well as the resultant cost incurred remains a source of concern for photovoltaic research[4,5,6]. It is indeed an undisputable fact that silicon is the most cost effective and most abundant material available on the earth's crust[7].

However, very little attention has been devoted to the dynamics of the signals emanating from a photovoltaic cell, though the analysis of the solar flux in longer timescales (monthly and annually) have been shown to have a chaotic/stochastic behavior[8]. It has been well established that the open circuit voltage of a photovoltaic cell comprises of a DC value with a highly unstable, fluctuating offset[8,9]. An understanding and thorough investigation into the dynamics of the offset has two principal applications:

1. Rather than averaging the offset as done in the case of inverter connected photovoltaic cells, the offset dynamics can be characterized and proper synchronization/equalization techniques can be used to enhance the solar cell output[10,11].
2. Since the offset dynamics are dependent on environmental properties, the photovoltaic cell can be used as a tool to study various atmospheric, solar and cosmic phenomena, such as solar flares, disturbances in the earth's magnetic field and so on[12,13,14]. The rationale here is that though the polysilicon photovoltaic cell is sensitive to a narrow range of the electromagnetic spectrum covering visible and ultraviolet light, higher frequency photons coming from sun and other cosmic sources could undergo nonlinear mixing in the sources themselves as well as atmosphere, to give Raman-type lower frequency components falling in the sensitivity window of the solar cell[15,16,17]. The signals thus detected would be sources for studying the processes and mechanisms giving rise to them.

The present work purports to an investigation into the offset dynamics of photovoltaic signals. Specifically, the open circuit voltage waveform of a rated solar cell is studied. It is observed that the signal contains chaotic components, and to understand this, various nonlinear parameters such as Lyapunov Exponent and Fractal Dimension are measured[18].

2. Methodology and Results:

A 6V, 50mA polysilicon photovoltaic cell is taken and the open circuit voltage is measured and recorded with the help of a digital storage oscilloscope (Tektronix TBS 1052B). The experimental setup is as shown in Fig. 1.

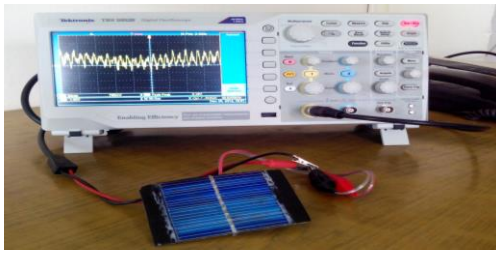

Figure 1 The experimental setup used for solar cell open circuit voltage characterization

Three illumination conditions are considered: Direct Insolation 'Bright' case (600-800 W/m^2), Tubelight diffused illumination 'Secondary' case (70-100 W/m^2) and 'Dark' Case (0-30 W/m^2).

For each case, the open circuit voltage waveform 'V_{oc}' is recorded, and analysis is done. The analysis consists of the time series waveform, magnitude spectrum, polar plot and the phase portrait. While the time series gives a rough idea of the fluctuations, the Fourier Magnitude spectrum and the polar plot helps to distinguish between the noise floor and the chaotic components present in the waveform[19]. The phase portrait outlines the dynamic behavior of the system[20]. These plots are shown in Fig. 2 for the diffused light scenario case.

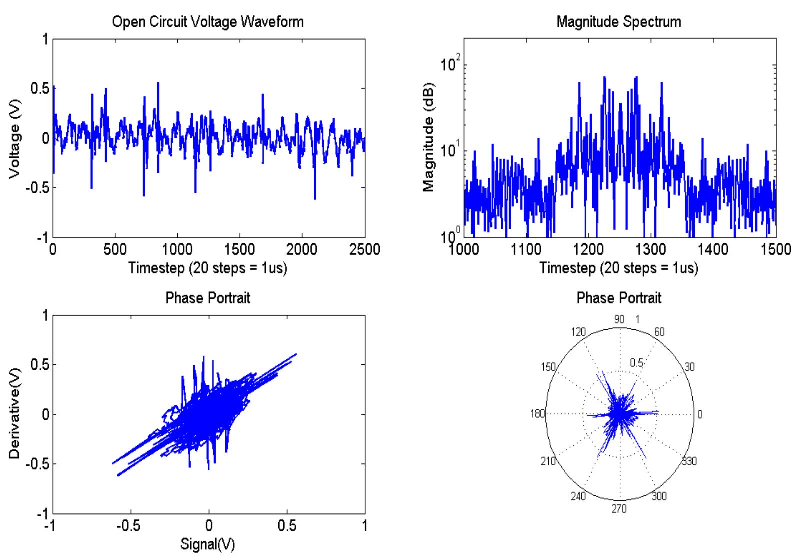

Figure 2 Open Circuit Voltage offset analysis for diffused light scenario

From the time series waveform, it is evident that the offset fluctuations are limited to 1V, less than 12% of the maximum rated voltage of 6V. The magnitude spectrum shows a wide band much above (50dB) the noise floor, and the same is also observed in the spikes in the polar plot spaced 60 degrees apart. Both these facts clearly establish the wideband behavior in the photovoltaic open circuit voltage. The phase portrait shows rich dynamics typically observed in high dimensional chaotic systems such as Electroencephalograms (EEG)[21,22].

In order to study the effects of frequency mixing and other related nonlinearities such as intermodulation and cross modulation in either the environment or the solar cell, the bispectrum is plotted. The bispectrum is the spectrum obtained from the third order cumulant, and for any two frequencies f_1 and f_2, gives the corresponding components as well as the coupled components of the form f_1+f_2 [24]. The bispectrum of the diffused light case is shown in Fig. 3.

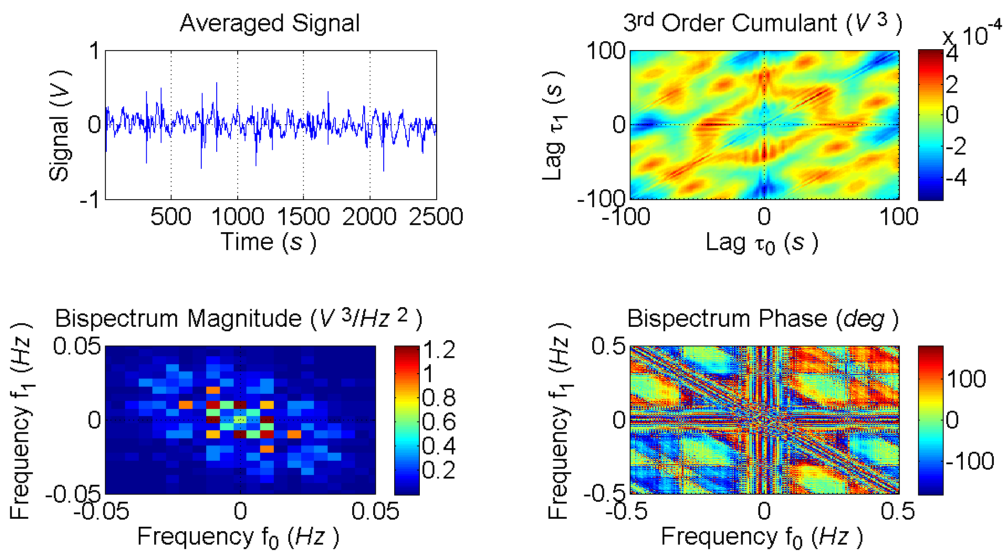

Figure 3 Magnitude and Phase Bispectrum for the Diffused Light Scenario

The contours of the bispectrum magnitude clearly highlight the presence of cross coupling components between the normalized frequency ranges of -0.03 to 0.03. Also, the phase bispectrum shows interesting patterns characteristic of chaotic systems[21,22].

In order to ascertain the presence of chaos, nonlinear analysis is performed for the Open circuit Voltage signal. The main parameters obtained here are the Kolmogorov Entropy '*K2*', Fractal Dimension '*D2*' and the Largest Lyapunov Exponent *'LLE'* of the signal.

The Kolmogorov entropy (*K2*), measured in information units of nats per symbol denotes the entropy and thus the uncertainty present in the signal, and large values indicate more dynamic and unpredictable behavior[25]. The Fractal Dimension (*D2*) is calculated using the Minkowski Bouligand Box Counting Algorithm and indicates the dimensionality of the chaos; higher the dimensionality, higher the instability[26].

Finally, the largest Lyapunov exponent (*LLE*), denoting the sensitive dependence of the system to initial conditions, is a definite and assertive test of chaos[27]. In the present work, the Rosenstein's algorithm is used to calculate the Lyapunov exponent from the time series[28]. Firstly, the divergence 'd' between nearest trajectories after an evolution time *t* is defined and the '*i*'th sample of *d* for the '*j*'th trajectory is calculated in Equation (1).

$$d_j(i) = C_j e^{\lambda_1 (i\Delta t)}; d(t) = Ce^{\lambda_1 t} \quad (1)$$

Here, '*C*'s are the normalization constants for the separation of neighbors and *λ*'s denote the Lyapunov exponents.

The obtained values of *K2*, *D2* and *LLE* for the bright, secondary and dark cases are shown in Table 1, along with the measured open circuit voltage and short circuit current values. All the values reported here are averaged values over twenty datasets taken at different times of the day.

Table 1 Values of Kolmogorov Entropy (*K2*), Fractal Dimension (*D2*) and Largest Lyapunov Exponent (*LLE*) obtained for the three test cases of Direct Insolation (Bright), Diffused Lighting (Secondary) and Dark cases

Parameter	Bright	Secondary	Dark
Open Circuit Voltage (DC)	5.25V	1.8V	0.7V
Short Circuit Current	24mA	320uA	10uA
K2 (Nats/Symbol)	17.3975	11.632	7.323
D2 (Dimension)	0.9863	0.9569	0.9684
LLE	7.2438	10.0791	7.2529

The non-integer values of fractal dimension, (close to unity) obtained for all three test cases and the corresponding positive Lyapunov exponents clearly assert the presence of a highly dynamic, unstable chaotic behavior of the photovoltaic open circuit voltage. This is in clear contrast with the general assumption of the dark current being caused due to noise[29]. Furthermore, the observed behavior also does not match the statistics reported of diode characteristics, such as avalanche breakdown[30].

The investigation of chaotic dynamics in the open circuit voltage, as outlined above, enables potential efficient synchronization schemes to enhance the solar cell output. Specifically, the characteristics obtained from the bispectrum can be studied for variation of cross-coupled frequency components for different illumination levels. The resulting inferences can then be used to establish a slave signal based control/synchronization using the photovoltaic signal as the master[31,32]. The resultant would be an enhanced photovoltaic output with useful utilization of the fluctuating offsets, and such an enhancement could be a supplement to the efficiency enhancement provided by higher generations of photovoltaic materials.

Another significant application of the chaotic dynamics investigation in solar cells is in using the photovoltaic cell as a tool to study atmospheric and cosmic effects. Though a detailed formulation and experimentation of such a study await, the authors attempted a preliminary experiment. Specifically, the authors took note of the solar flare activity prominence predictions on the 20:30 UT, 14th of December, 2014 as witnessed from X-Ray diffraction data, and measured the open circuit spectrum at the above mentioned time. This spectrum was compared with a similar reading during a remarkably low flare activity[12,13,14]. The whole experiment was carried out indoors during nightfall to rule out illumination based false readings and minimize thermal phonon effects. The open circuit spectra during high and low flare activities are compared in Fig. 4.

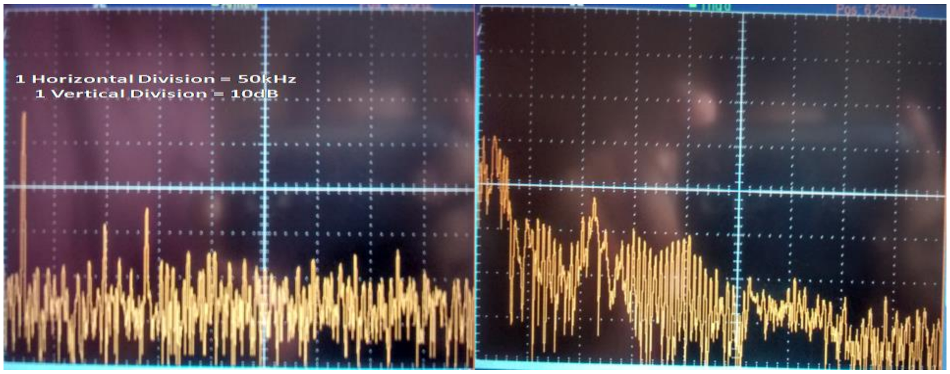

Figure 4 Comparison of Open Circuit Voltage Fourier Spectra during low solar flare activity (left) and high solar flare activity (right)

The presence of significant peaks in the vicinity of 200kHz for high solar flare activity does ascertain the possibility of the photovoltaic cell being used as a tool to study atmospheric and cosmic effects[12,13,14]. The highlight of such a study would be in properly segregating the various frequency components present in the signal and identifying them with the cosmic event giving rise to them, a novel kind of chaotic spectroscopy.

3. Conclusion

The characterization of the open circuit voltage of a photovoltaic cell using nonlinear analysis parameters, clearly ascertaining the underlying chaotic dynamics, and the possibility of such an investigation leading to enhancement of solar output power as well as a potential candidate tool for studying atmospheric and cosmic effects forms the highlight of the present work.

Appendix:

Materials and Methods:

All the experiments reported in the present work were performed using a rated photovoltaic cell of 6V, 50mA at 1000 W/m^2. The oscilloscope is well calibrated to eliminate false positives, and the nonlinear analysis parameters reported are those obtained as the average over 20 readings for each case. The various readings were taken on a distributed timescale from June, 2014 to December, 2014, in the geographical location of Thanjavur, TamilNadu, India (10°46’56.99”N; 79°7’52.51”E, 88m elevation).

The three cases of illumination were taken in the following manner:

1. Direct Insolation, corresponding to ‘bright’ case was taken with direct exposure to the sun, accounting for nearly 600-800W/m^2 .
2. For the diffused lighting ‘secondary’ case, a 100W tubelight was used in a roomlit condition.
3. For the ‘dark’ condition, all lighting was eliminated, and the readings were taken in a completely dark room.

Supplementary Plots:

In this section, the offset analysis and bispectrum plot for a selected case each of bright and dark insolation is provided.

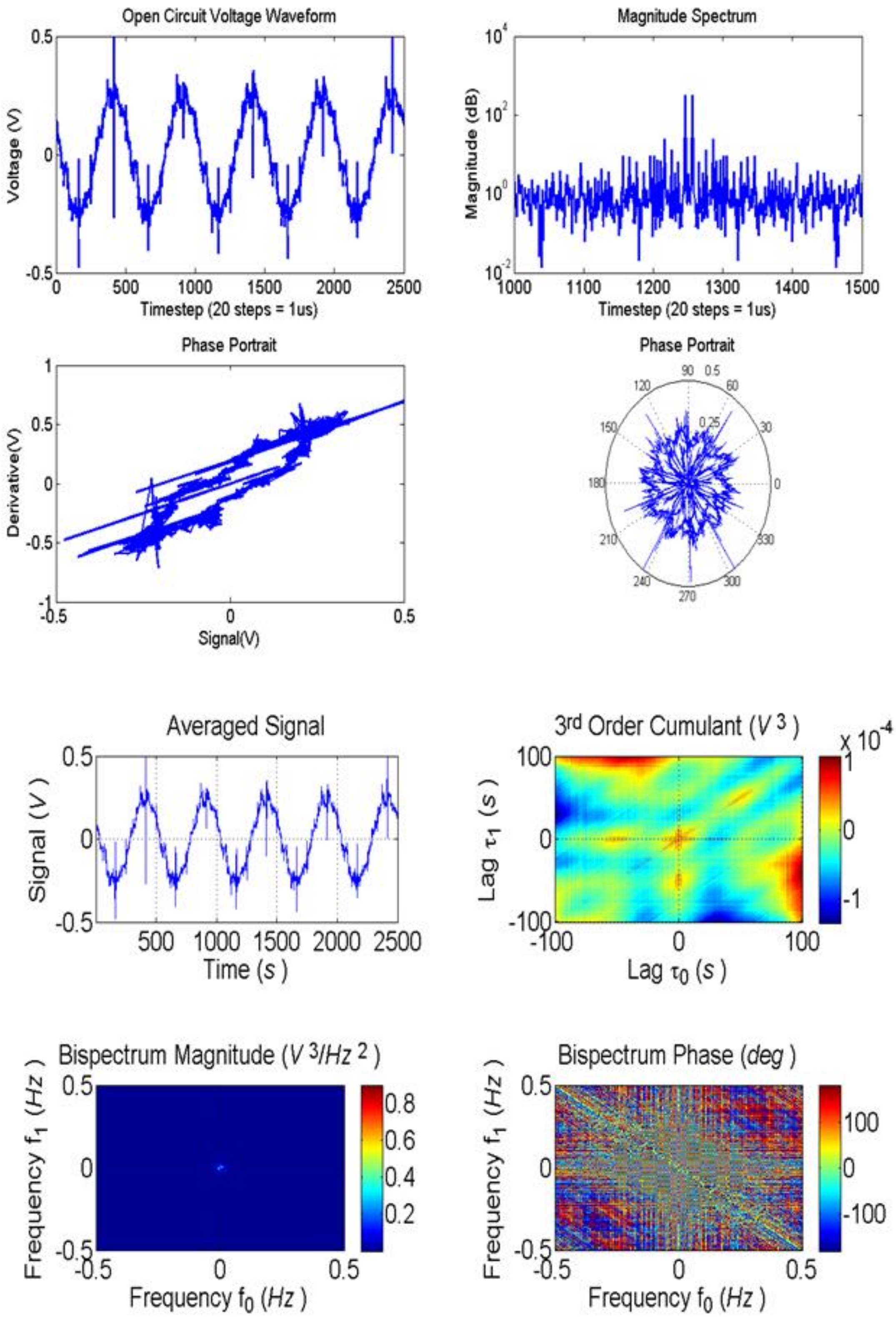

Figure 5 Offset Analysis and Bispectrum Plots for Bright Insolation

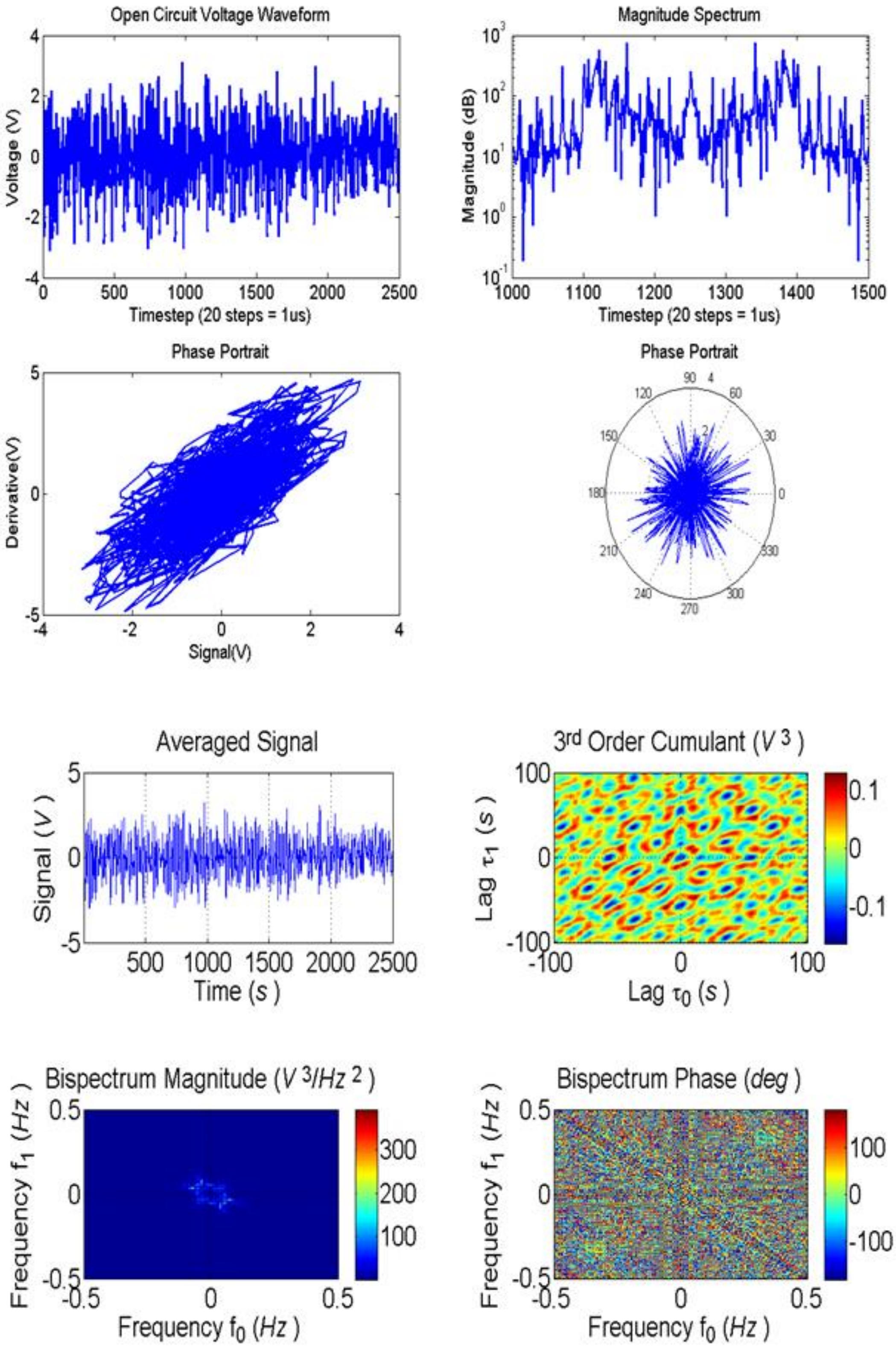

Figure 6 Offset Analysis and Bispectrum Plots for Dark Insolation

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