ISSN: Printed: **3078-9656, Online: 3078-9664**, paper ID: 101

Spectral Analysis of Solar Energy Technologies: Integrating Renewable Energy Sources into Electrical Networks

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Article Info

Article history:

Received Sept., 06, 2025
Revised Nov. 20, 2025
Accepted Dec., 10, 2025

Keywords:

Solar photovoltaic
Spectral analysis
Grid integration

ABSTRACT

Solar photovoltaic (PV) technology is becoming more important in modern energy strategies, because of their scalability and affordability. However, they also have shortcomings such as voltage fluctuations, harmonic distortion, and reduced inertia, and instability due to weather. These technical challenges can be assessed using spectral analysis methods such as Fourier and harmonic decomposition, which helps solve these problems. This paper summarizes recent research, linking solar energy sources with electrical sources using advanced power electronics, intelligent inverters, hybrid storage systems. Findings suggest that we can detect flicker, and small-signal instabilities with spectral methods, and that integrating them with hybrid systems increases the reliability and sustainability of the grids.

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1. Introduction

The recent years are witnessing a large-scale transformation in global energy systems, and solar photovoltaic (PV) power is the leading force of this shift. Between 200 and 2020, the capacity of PV has grown from small technology with less than 5 GW to a primary source of power with more than 705 GW worldwide. It is expected that this capacity will reach around 8500 GW by 2050 [1], which is sufficient to compete with the entire current carbon-based fuel systems. This growth of PV offers socio-economic and environmental benefits and they contribute to the international decarbonization actions, which reduces fossil imports, and offers new jobs and opportunities. On the other hand, PV operated differently from the traditional electricity systems, because PV relies on inverter-based connections; making it variable, and dependant on irradiance and weather patterns. These features of PV lead to harmonic pollution, reduced inertia, and voltage swings [2]. The integration of PV into modern electrical networks is not a simple task, and requires systemic solutions such as grid reinforcement, advanced inverters, and energy storage installations. Recent studies show that there are still unresolved issues when integrating PV into electrical networks: voltage fluctuations, congestion, and coordinating protection systems [3]. These challenges can be mitigated using spectral analysis techniques, that allow us to decompose the signal into frequency components. These techniques include Fourier Transform (FT), Wavelet Transform (WT), and harmonic decomposition. They reveal some insights that help operators to solve problems such as oscillations, and design appropriate integrating strategies. In this paper, we build on a multi-dimensional framework to understand how solar PV can be integrated in electrical systems. We combine technical spectral analyses of disturbance with enabling technologies such as advanced power electronics. In addition, we mention socio-environmental insights including emissions reduction and employment. By combining these domains, the study puts spectral analysis as mathematical method that bridges the gap between system planning, and innovation.

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2. Background and Related Work

2.1 Evolution of PV Integration Research

In the last two decades, more and more research has been done to explore the effects of solar PV when integrated in electrical networks. This exponential growth led to more than 7,000 publications between 2000 and 2021. In general, the literature focused on area such as power quality, stability, and energy management. In addition, there has been an increasing attention toward hybrid systems and intelligent inverter control, because inverters are the building block of PV technologies [1].

2.2 Harmonic Distortion and Power Quality

Inverter-based PV systems have an apparent problem that affects the overall performance of the network. This problem is harmonic distortion, which is harmonic currents flowing through the network due to the existence of switching devices and nonlinear control units. Many studies of distribution feeders state that the Total Harmonic Distortion (THD) and individual harmonic distortion are rising with the increasing number of PV networks and utilities at rooftops. Sometimes, these distortions are larger than IEEE 519 thresholds [4]. The use of spectral methods like Fourier Transform (FT) is essential to monitor these harmonics and verify how much they comply with planning levels.

2.3 Voltage Flicker and Mid-Frequency Variability

Voltage flickers is another problem that faces PV networks, it happens because of rapid irradiance changes, due to external factors such as passing clouds. Rapid irradiance causes oscillations in frequency of the network (0.1 – 10Hz) which in turn leads to voltage flicker. The study [5] shows that weak feeders that use clustered rooftop PVs experience voltage flicker that is linked to sudden irradiance changes. To measure the amount of flicker a system imposes, we can use Short-Time Fourier Transform (STFT) and Wavelet Transform (WT). Some studies state that WT outperforms STFT in capturing localized events. This enables us to quantify flicker severity in the time-frequency space [6].

2.4 Reduced Inertia and Small-Signal Stability

Reduced Inertia happens when integrating PVs in the network, which causes shifts in the synchronous generation, and reduces the natural inertia and damping. In large systems, we notice poor damping of 0.2 -1 Hz oscillatory modes when PV penetrating rises. These measurements are done using modal analysis of transmission grids [7]. In addition, the existence of inverter controls like PLL and current loops affects the grid impedance, which creates low-damping modes in distribution systems [8] . To mitigate these shifts, engineers use Eigenvalue-based spectral analysis, and impedance Bode plots as they can quantify these shifts properly.

2.5 Resonance and Impedance Interactions

Resonance is a phenomenon that occurs when inverter control impedances align with the resonant frequencies of the feeder in PV network, resulting in a harmonic resonance that can reduce the efficiency of the network. Case studies show that the amount of resonance increases in weak grids, leading to degradation of Power Quality (PQ) and even failure of protective elements in the network (protective relay). To lower harmonic resonance, we can add tuning filters, damping loops, and impedance shaping by control design [9].

3. Spectral Analysis Framework

Spectral analysis is used to measure the impacts of solar PV integration on electrical networks. Unlike time-domain methods, which capture disturbances as they occur, spectral tools provide a way to capture where in the frequency spectrum the distortions are occurring, and how they affect the grid. In this section, we discuss widely used spectral methods: Fourier analysis, wavelet transform, and eigenvalue spectral analysis.

3.1 Fourier Transform and Harmonic Analysis

The Fourier Transform (FT) is still the principal method for assessing the quality of power networks in PV systems. FT decomposes current of voltage into sinusoidal signals, and can be used to quantify Total Harmonic Distortion (THD) and individual harmonic orders.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\% \tag{1}$$

where V_n are the harmonic voltages and V_1 is the fundamental component.

Studies of grid-connected PV have shown that harmonic orders at 3^{rd}, 5^{th}, and 7^{th} are dominant, with THD increasing with penetration [10]. THD values are compared against IEEE standards, which sets voltage THD limits to be less than 5%.

3.2 Wavelet and Time–Frequency Methods

Although FT is beneficial in in capturing total distortion, it cannot capture fast irradiance ramps or short-term flickers in the network. For this, we can apply time-frequency methods such as Short-Time Fourier Transform (STFT), and Wavelet Transform (WT).

In Short-Time Fourier Transform (STFT), we slide a fixed window over the signal, capturing both time and frequency features.

$$X[m,k] = \sum_{n=1}^{N-1} x[n]\, w[n-mH] e^{-j\frac{2\pi}{N}kn} \qquad (2)$$

where:

- w[n] window of length L (Hann, Hamming, etc.),
- m: frame index,
- H: hop size (shift between consecutive windows),
- k: frequency bin,
- X [m, k]: STFT matrix (time–frequency representation).

This is useful for detecting flickers in the network but it still has shortcomings like the trade-off between time and frequency resolution. In other words, if we want accurate frequency measurement, we need to increase the window size, which results in fewer time measurement accuracy, and vice-versa. Wavelet Transform (WT) is used to detect localized fast transient and mid-frequency oscillations. It provides multi-resolution analysis and is used in cloud-driven PV changes. In terms of flicker severity, WT outperforms STFT [11]. In practice, WT scalograms isolate ramp events and abrupt changes in frequence, which allows for the detection of flickers.

3.3 Impedance and Eigenvalue-Based Spectral Analysis

In addition to harmonics and flicker, PV systems also suffer from stability issues because of the interaction between inverter control loops and network impedance. These interactions cannot be captured with STFT and WT; Instead, we use impedance-based and eigenvalue spectral methods:

- ***Impedance modelling:*** represents both converter and the grid as impedances in the network. Instability occurs when the impedance of the converter intersects the impedance of the network in critical bands [12].

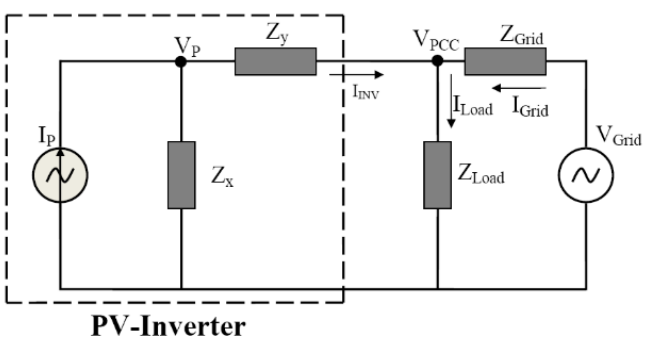

Figure 1: Equivalent circuit of a PV grid-connected system [13].

- **Eigenvalue spectral analysis:** by analysing the eigenvalues of the covariance matrix of PV signals to identifies shifts in oscillatory modes under high penetration., Using eigenvalues we can see that reduced inertia decreases the damping of small-signal oscillations [14]

Dijlah Journal of Engineering Science (DJES) Vol. 2, No. 4, December, 2025, pp. 269-275
ISSN: Printed: **3078-9656, Online: 3078-9664**, paper ID: 101

3.4 Suggested Workflow for PV Spectral Analysis

To summarize, spectral analysis of a PV network can be done following these steps:

1- Data acquisition: collect voltage and current waveforms at the point of common coupling.

2- Fourier analysis: Compute THD and individual harmonics, and compare them against IEEE benchmarks.

3- Wavelet analysis: apply WT to capture flicker or ramp events in the network.

4- Impedance/eigenvalue analysis: Model the inverter and feeder impedance, and identify resonance and low-damping modes through eigenvalue scans.

5- Control: In this step, we retune the filters, and change inverter control loops.

6- Verification: we perform the spectral analysis once again to check the performance.

4. Effects of PV Integration on Network Performance (Spectral View)

In this section, we mention the challenges associated with integrating PV systems in to electrical grid networks. These challenges arise due to inverter-based nature of PV systems, their variability, and how they interact with the infrastructure of the gird. We will mention the performance challenges and how they impact the overall performance of the electrical network.

4.1 Harmonic Distortion

One of the main issues in PV feeders is the injection of harmonics from inverters, happening because of the switching operations and nonlinear controls leading to harmonic orders (3^{rd}, 5^{th}, 7^{th}, 11^{th}), which accumulate with the increase in PV penetration. These distortions lead to overheating and failure of protection devices, and introduce additional losses.

4.2 Voltage Flicker and Fast Irradiance Variability

When the voltage of the PV system flickers, it disrupts sensitive equipment and appliances. These flickers could happen because of oscillations in the frequency, caused by power ramps in the PV plate. One obvious reason of power ramps is passing clouds that causes sudden changes in PV output. Flickers reduce power quality and may cause malfunction, especially in devices that require stable voltages.

4.3 Reduced Inertia and Frequency Instability

Unlike synchronous machines, PV inverters do not provide rotational inertia. When conventional plants are diplaced, the grid's natural ability to resist frequency deviations declines. Therefore, small disturbances can now lead to larger swings in frequency, especially in the 0.2-2 Hz range.

4.4 Resonance Phenomena

When the inverter harmonic emissions are equal to the natural resonant requencies of the network, resonance happens, leading to amplified oscillations, voltage distortions, and damage of protective relays. Weak grids are especially prone to this type of resonance, which demands better filter tuning and impedance shaping [15]

5. Mitigation Strategies for PV Integration Challenges

In this section, we discuss possible ways to mitigate the impacts of integrating PV systems with electrical networks to maintain power quality and stability. These solutions combine hardware and control ideas, based on the spectral analysis tools we discussed in section 3.

5.1 Harmonic Mitigation

1. **LCL Filters:**
They are used a lot in PV inverters to attenuate high-frequency harmonics. They are third order passive filters installed between the inverter and the grid. Their performance rely on grid impedance; and they need to be tuned slightly below the switching frequency. Also, they typically include damping resistors added to

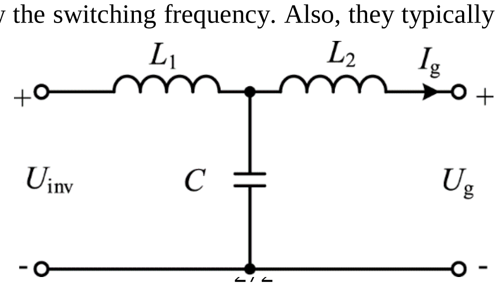

Figure 2: design of LCL filter

control the resonance.

2. **Active Power Filters (APF):**

Instead of attenuating harmonics, APFs use compensating currents to cancel them, they can be adaptable and counteract multiple harmonic orders at the same time. These filters are useful in feeders with mixed loads.

3. **Inverter Control-Based Mitigation**

   Other solutions include Pulse Width Modulation (PWM) to lower specific harmonics at the source using digital controllers. They allow real-time control and can be used instead of passive filters that are only set once and are not adaptable [16].

Flicker Control

1. **Ramp-Rate Control:**

To lower flicker rates, modern PV inverters limit the rate of power change over time, and smooth output ramps that are caused by passing clouds. Depending on grid codes, ramp-rate limits range from 10% per minute to 20% per minute of rated capacity.

2. **Short-Term Energy Storage:**

The use of batteries and supercapacitors can be used to limit fluctuations and flicker in voltage, and therefore they can smoothen power output.

3. **Spectral Forecasting with Wavelets:**

we can use WT to analyse PV variability and predict flickers, therefore spectral forecasting is crucial to enhance the performance of PV systems and lower flicker rate.

Stability Enhancement

1. **Grid-Forming Inverters (GFMI):**

these types of inverters are used to stabilize weak grids because they set their own voltage and their own frequency references. In their core, they operate as a virtual synchronous machine (VSMs).

2. **PLL Tuning and Virtual Damping:**

Phase-Locked Loops (PLLs) are devices used in inverters to improve frequency tracking and at the same time not amplifying the oscillations.

3. **Synchronous Condensers:**

These devices are used with inverter-based resources and they provide an actual rotating inertia and voltage support. On the down side, these condensers are considered expensive.

Resonance Suppression

1. **Impedance Shaping:**

By performing impedance shaping, we can ensure that converter-grid impedance do not overlap at any critical points, and we an adjust inverter control loops by changing controllers or adding virtual impedance to shift resonance frequencies away from dominant harmonics.

2. **Active Damping Controls:**

As mentioned earlier, we can use active damping instead of passive damping to lower resonance without increasing the losses in the network. Therse inverters inject corrective signals to lower oscillations.

Table 1 : PV Integration Challenges Summary

Challenge	Impact on Grid	Spectral Indicator	Method	Typical Mitigation
Harmonic Distortion	Overheating, relay failure.	THD, individual harmonics	Fourier Transform	LCL filters, active damping
Flicker (Cloud Ramps)	Poor voltage quality, user discomfort	Mid-frequency (0.1–10 Hz) energy	Wavelet Transform	Ramp-rate control, storage
Reduced Inertia	Poor modal damping, unstable modes	Eigenvalue spectra, damping ratios	Eigenvalue/Impedance Analysis	Grid-forming inverters, virtual inertia
Resonance	Amplified oscillations, PQ degradation	Impedance crossings, resonant peaks	Impedance Bode plots	Impedance shaping, filter retuning

6. Limitations & Future Work

Although spectral methods can be efficient in solving problems of PV systems, there are still limitations related to the lack of high-resolution measuring devices and real-time spectral monitoring. In addition, there is limited access to datasets and this will block the ability to compare and analyse results. Also, many inverter models use simplified control dynamics depending on steady-states of the system, and they ignore time-frequency events (flicker, interharmonics). This makes it harder to capture nonlinearies and unbalance in the network. In addition, Wavelet Transform and other spectral techniques requires computationally-heavy calculations and they are considered resource-intensive, and therefore they cannot be used for real-time monitoring or control. Finally, most studies focus on PV alone, without considering the hybridized with wind and storage versions. Future work should address these gaps by developing accessible monitoring systems, improving model fidelity, expanding standards to include spectral indices, accelerating algorithms for real-time use, and extending analysis to hybrid multi-inverter networks.

7. Conclusion

In this paper, we discussed the integration of solar PV into electrical networks. PV delivers clean energy but at the same time it introduces new performance challenges, including harmonics, flicker, and resonance. We used spectral analysis methods to study these challenges, and then proposed mitigation strategies such as LCL filters, ramp-rate control, and others. Ultimately, spectral analysis provides foundation for PV networks and it ensures that power quality and stability is maintained, especially in our era, where the renewable penetration continues to grow and replace standard networks.

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Sarmad Mohammed Ayoob Al-Khafaji is an Electrical Engineering graduate from the University of Babylon. He possesses professional experience in the supervision and management of multiple sewage lifting station projects in Karbala Governorate. His duties included providing electrical supervision for the implementation of the stations and implementing control systems based on PLCs (Programmable Logic Controllers) to operate the stations.

He has also implemented innovative solutions to enhance energy efficiency by utilizing PLC devices and has participated in engineering workshops and seminars. His technical skills encompass programming Siemens and Schneider PLCs, implementing control systems , and utilizing software such as MATLAB, LabVIEW, and Microsoft Office.

Engineer Sarmad is proficient in Arabic and has intermediate proficiency in English. He also possesses various skills, including problem-solving , leadership , project management , and teamwork