Tagung Zukünftige Stromnetze | Future Power Grids Conference 2024
The Structure of the Future Energy System
https://doi.org/10.52825/zukunftsnetz.v1i.1041

Published: 16 May 2024

Impedance-Based Method for Predictive Stability Assessment

A Review

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Abstract. Impedance-based analysis methods enable a more specific and earlier foundation for assessing harmonic stability in decentralized converter-based power plants compared to the conventional compliance testing in the grid connection process. Essentially, they can be implemented as black-box model approaches without the necessity to disclose internal control models. Initially, only knowledge of the input impedances of the planned grid connection point and the planned PV system is required for application. For this purpose, the method of impedance spectroscopy for inverters has already been developed as a means to determine the effective impedance profile and the internal harmonic sources of inverters, allowing for the description of the frequency-dependent behavior of individual units. The time- and frequency-dependent grid impedance at the grid connection point (GCP) has also been successfully measured in several campaigns on medium and low-voltage grids. Through the coordinated application of both measurement methods, a predictive harmonic assessment is intended in the future, ensuring high planning reliability and grid quality even in grids with a high penetration of power electronics-coupled systems. This paper provides an overview of the current state of research on impedance-based stability criteria and presents measurement methods for practical implementation. Furthermore, it outlines remaining open questions until application in the field.

Keywords: Harmonics, Stability Criterion, Impedance Spectroscopy, Grid Impedance Measurement, Grid Connection Assessment, PV Power Plants

1. Introduction

Harmonics induced by the pulsed operation of power electronics-coupled consumers and sources in the grid are becoming an increasingly prominent issue [1, 2]. Limiting these harmonics is a crucial goal in the transformation of our electrical energy system [3]. Unlike conventional large power plants, PV power plants are constructed from a multitude of generating units. The electrical characteristics at the GCP primarily result from the technical properties of the employed inverters and their interactions. Furthermore, internal power cabling and transformers play a decisive role in this context. To date, standardization does not offer adequate solutions for the stability and harmonic analysis of such complex systems connected to the grid [4, 5]. This is evidenced, among other factors, by undesired resonance effects or high harmonic distortion levels that persist despite comprehensive grid connection procedure [6, 7]. Approaches to solve this issue promise impedance-based methods, which enable a predictive assessment of harmonic stability. The impedance-based stability criterion is the subject of research in numerous fields and will be explained hereinafter using PV power plants as an example, presenting the current state of the technology in this regard.

2. Voltage Quality and Stability

Ensuring voltage quality compliance according to DIN EN 50160 is verified during the grid connection process when connecting new installations to the public grid [8, 9]. Particularly in the conformity assessment of network impacts due to the emission of harmonics into the grid, assumptions are made that often inadequately or incorrectly describe system behavior, potentially leading to incorrect evaluations in the assessment [5, 10, 11, 12, 13]. Some of these highly simplified assumptions include:

- inverter behave like ideal harmonic sources,
- phase information is not considered during the characterization,
- emitted harmonic currents are always destructive,
- the behavior of the power plant can be described by the linearized behavior of the generating units based on the planned plant capacity,
- the qualitative profile of the network impedance spectrum is generally standardized and
- the harmonics affecting the inverters in the grid cannot be accounted for.

Methods such as the „Voltage-Current Ratio Difference Method“ take a step further by enabling the attribution of both the cause of harmonic currents at the interconnection point of the system or the grid and the identification of dominant sources [14, 15]. The procedure, however, relies further on the premise that the installation has already been constructed to consider coupling effects between units, thus rendering it unsuitable as a predictive method. Simulative methods for evaluating the frequency-dependent robustness of the network, which extend beyond a linearized assessment of short-circuit power, are also under current investigation [13]. A controller-based stability assessment allows for the simulation-based detection of grid instability in grid-tied renewable energy resources during the planning phase. However, these methods require precise information regarding the design of the renewable energy resource and the planned network connection point, which are often unavailable. An alternative approach is provided by impedance-based stability assessments [16].

2.1 Impedance-Based Stability Criterion

In stability assessments of grid-tied power plants involving Renewable Energy Sources (RES), a fundamental distinction can be made between source-driven and resonance-driven harmonics. Impedances and harmonic sources must be considered in a frequency-dependent manner in both cases.

Source-driven harmonics arise from the current flow due to the voltage difference and the combined impedance of both sources (grid and RES). These source-driven harmonic currents are limited by the power of the voltage sources and the non-zero impedance of the grid. Nevertheless, they can still cause significant voltage distortions [10]. In order to assess interactions, it is essential to understand the internal harmonic sources of the planned RES before connecting them to the grid. Through differential impedance spectroscopy, both the internal harmonic sources and the input impedances of the RES can be determined using measurement techniques [17].

Significantly large harmonic currents can arise when the sum of the impedances of the grid and the RES approaches zero. This scenario occurs when the magnitudes of the impedances are equal but with a phase shift of 180° (e.g., a capacitive inverter and an inductive grid). Even very small harmonic sources in the system can lead to resonance oscillations and, in the worst-case scenario, cause damage to the RES and other components [10].

To detect such resonance effects, current research is investigating the application of impedance-based stability criteria [16, 17, 18, 19, 20].

Unlike controller-based stability assessments, impedance-based stability evaluations do not require precise information about the design of the RES. The stability condition can be checked solely based on the input impedance of the RES and the network impedance [16]. Both systems are initially characterized as frequency-dependent Thevenin or Norton equivalent circuit diagrams (ECDs) for this purpose. A conversion between these two ECDs is feasible [10].

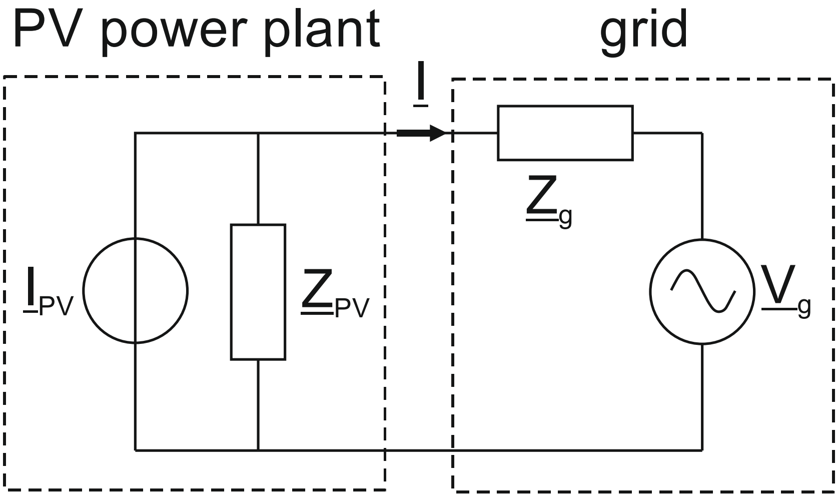

Figure 1. *Small-signal equivalent circuit for stability analysis of an inverter-based system connected to the grid.*

Possible measurement methods for determining the parameters of the ECDs are presented in this paper.

The impedance-based stability criterion represents a specific application of stability conditions derived from linear control theory [16, 21]. The grid is fundamentally characterized as a real voltage source. Conversely, photovoltaic (PV) RES are often controlled as current sources [16, 22]. Their internal harmonic sources, on the other hand, behave like voltage sources [17, 23]. Figure 1 depicts the small-signal ECD for assessing the stability of a grid-following PV inverter connected to the grid.

$$\underline{I}(f) = \frac{\underline{I}_{PV}(f) \cdot \underline{Z}_{PV}(f)}{\underline{Z}_{PV}(f) + \underline{Z}_g(f)} - \frac{\underline{V}_g(f)}{\underline{Z}_{PV}(f) + \underline{Z}_g(f)} \tag{1}$$

$$\underline{I}(f) = \left[\underline{I}_{PV}(f) - \frac{\underline{V}_g(f)}{\underline{Z}_{PV}(f)}\right] \cdot \frac{1}{1 + \frac{\underline{\boldsymbol{Z}}_{\boldsymbol{g}}(\boldsymbol{f})}{\underline{\boldsymbol{Z}}_{\boldsymbol{PV}}(\boldsymbol{f})}} \tag{2}$$

The output current of the inverter is calculated according to the ECD using formula (1) and can be rearranged following equation (2). It is assumed fundamentally that each source is individually stable when unloaded. The stability of the inverter connected to the grid is therefore contingent upon the right term in equation (2). This resembles the closed-loop transfer function of a negatively feedback-controlled system, where the feedback gain is $\underline{Z}_g/\underline{Z}_{PV}$. In accordance with linear control theory, the closed-loop transfer function is stable if the feedback gain satisfies the specific Nyquist stability criterion [16].

The impedance-based stability criterion is verified by examining the quotient of the grid input impedance $\underline{Z}_g$ and the inverter input impedance $\underline{Z}_{PV}$. The Nyquist stability criterion can be assessed in the Nyquist plot at the location -1 on the abscissa, which must neither be crossed nor encircled to fulfill the criterion. Additionally, verification can be conducted in the Bode diagram, commonly used to represent the frequency-dependent impedance of electrical energy systems. In reference [18], four general rules are graphically presented to illustrate the application of the impedance-based stability criterion in the Bode diagram for this purpose. However, this work is limited to depicting the quotient already calculated from the grid and RES impedances. In reference [17], the criterion is examined at the intersections of both impedances in the Bode diagram. This approach is particularly suitable for determining phase margins towards the critical point. Laboratory examinations of the impedance-based stability criterion have already demonstrated the relationship between low phase and gain margins towards the critical point and increased harmonic currents and voltages at the Point of Common Coupling (PCC) for the respective frequency ranges [17, 24]. This relationship also leads to the introduction of so-called „forbidden regions" [24, 25]. These regions are intended to ensure sufficient phase and gain margins, thereby ensuring stable operation at all times.

2.2 Added Value of Impedance-Based Grid Connection Planning

By using appropriate measuring instruments, this assessment method offers the potential for a more precise understanding of the grid connection point and the characterization of RES, as well as their interactions, without the need to disclose proprietary information. Harmonic stability can be predicted and evaluated, unlike in traditional compliance tests. This predictive assessment allows for the utilization of existing transmission capacities that have previously remained unused due to conservative estimations as per the Technical Connection Rules (TAR) Medium Voltage 5.4.4. [5, 16]. Likewise, countermeasures can be planned more precisely and calculated earlier in the plant design process. Moreover, even in existing facilities, the assessment method utilizing plant and grid impedance measurements can be employed to identify causes of unintended electromagnetic compatibility (EMC) issues [26, 27]. Source-driven harmonics due to internal harmonic sources within the RES can be specifically filtered out. Resonance-based harmonics, identified using the impedance-based stability criterion, can be avoided by adjusting the input impedance of the RES. This impedance is primarily influenced by the current control of the controller in the lower frequency range and by the passive output filter in the higher frequency range [17]. This allows for improving voltage quality through cost-effective adjustments using Impedance Shaping. For instance, voltage quality can be enhanced through software-based modifications to the current control system [28].

3. Previous Applications of Impedance-Based Methods

The consensus in research is that new methods are necessary to ensure high voltage quality, particularly amidst the energy transition and the extensive expansion of renewable energy facilities and storage systems [4, 29]. Different approaches have been proposed in this regard. For instance, in [30], an approach based on extensive measurement campaigns at the low-voltage level is presented for determining harmonic current limits between 2 and 9 kHz. The "Voltage-Current Ratio Difference Method" introduces a technique for identifying the relevant sources of harmonic currents [14, 15]. The following analysis primarily focuses on previous studies regarding the application of impedance-based methods.

It is noticeable that the current state of research is primarily characterized by partly simulation-based investigations and laboratory conditions [31, 32, 28]. Measurement campaigns, however, indicate that this assumption, especially for frequencies above 2 kHz, is not practical or realistic [30, 33].

The modeling of RES for determining impedances poses another challenge, and operating-point-dependent (OP-dependent) variations in RES impedance are still being overlooked [34, 31, 35]. In [36], a method is introduced that already considers the OP dependence of RES. However, it describes the OP dependence using a V/I characteristic based on controller regulation and short-circuit current considerations, thereby requiring detailed information about these systems. What is not considered in this method is the impedance of the RES, which is necessary for the application of the impedance-based stability criterion. Moreover, for a practical implementation of the criterion in the field, a distinction must be made between the stability of individual Energy Conversion Elements (ECE) and the overall Generating Unit (GU) [37, 38, 39]. By measuring the system impedance of the plant and grid impedance at the PCC on the medium-voltage level, the impedance-based stability assessment could be conducted for the entire GU. However, impedance measurements within the plant and of individual ECE enable an internal impedance-based stability assessment. Nevertheless, it´s important to note that this criterion alone cannot guarantee stable operation or predict resulting harmonics at the PCC for one or more inverters [40, 38]. Factors such as internal harmonic voltage sources should complement the stability and harmonic current/voltage assessment, thereby expanding and enhancing the procedure [10]. For a predictive assessment method, a consideration of the voltage sources of individual inverters and an impedance-based stability assessment for the planned power plant at the intended GCP would be appropriate.

Alongside investigating the root causes and assessing stability, research is also exploring solutions to enhance grid quality. Stability is expected to improve through measures such as Impedance Shaping or new control approaches aimed at optimized resistance-emulating control [28, 31]. The impedance of the inverters at the PCC is intended to be adjusted by intelligent control, ensuring it forms sufficient phase and gain margins towards the critical point when combined with the existing grid impedance.

The implementation of the stability criterion for three-phase energy systems represents another focal point research [41, 42, 43, 44]. Common transformations used for applying the impedance-based stability criterion are DQ-transformations and symmetrical components [34]. The choice of transformation method has so far depended on factors such as the background of the users and the intended application scenario. For instance, applications as stability monitoring systems are being examined [27, 26]. The approach described in [27] involves measuring the time-dependent grid impedance during operation by superimposing an additional wideband signal on the nominal output current of a three-phase inverter. The stability criterion is then directly examined based on the ratio of the measured grid impedance and the analytically determined inverter impedance. This allows for an “online” stability control for individual ECE. When determined in the DQ system, this approach simplifies the consideration of the measured grid impedance in the current regulation of the inverter. However, a challenge with this method is still the analytical determination of the inverter impedance, which is assumed in this application. Alternatively, this monitoring approach can be complemented in advance using differential impedance spectroscopy [34]. However, long-term measurements conducted at the medium-voltage level indicate that the time dependency of the grid impedance up to 9 kHz is largely cyclically pronounced [33]. Moreover, OP dependencies of the inverters and the scaling to the GU level have not been taken into account thus far.

In [39], a method for reverse impedance-based stability assessment is introduced. This methodology aims to support grid operations by examining the influence of removing individual units on overall stability. Potential scenarios could include technical failure of specific units or deliberate shutdown of facilities.

Although various applications for utilizing the impedance-based stability criterion are being researched, these investigations largely focus on simulations or laboratory-scale measurements. A practice-oriented field study using proven measurement methods and considering effects such as the time dependence of grid impedance, OP dependencies of inverters, and their scaling to the GU level, has not yet been established.

4. Impedance Measurement Methods

For the measurement-based determination of the frequency-dependent Thevenin ECDs of the inverters and the grid impedance of the GCP, necessary for stability assessment, state-of-the-art measurement devices already exist. These will be introduced below, accompanied by an explanation of the measurement methods.

4.1 Time- and frequency-dependent grid impedance measurement

Active impedance measurement methods all rely on exciting the Device Under Test (DUT) and precise current and voltage measurements [45]. Random Pulse Width Modulation (rPWM) excitation by switching an ohmic load has proven to be a particularly suitable method for rapid and mobile determination of impedances and resonances at the PCC [46, 47].

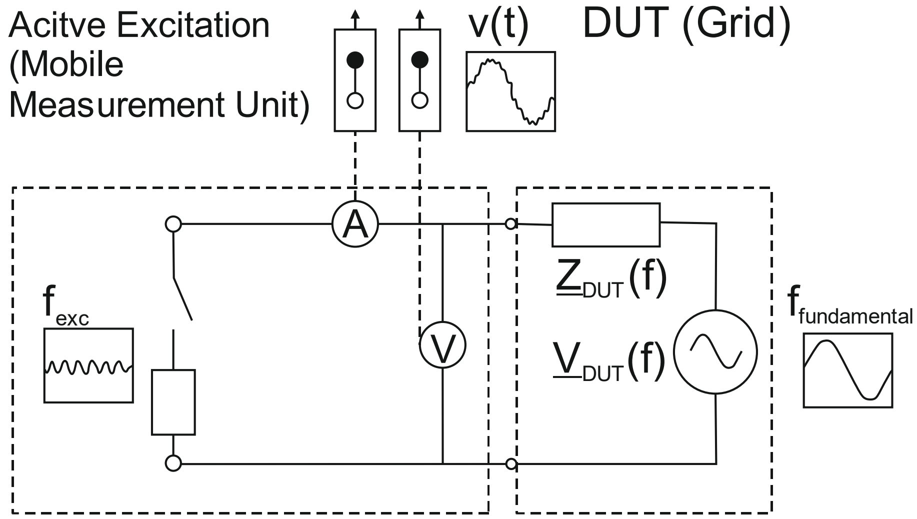

Figure 2. *Schematic representation of the mobile measurement method utilizing rPWM excitation.*

Figure 2 schematically represents the measurement setup. The measurement device is connected to the PCC under examination, and an ohmic load is pseudo-randomly pulsed onto the grid via a power electronic switch. The resulting excitation current through the measurement device and the voltage response at the PCC are then evaluated in the frequency domain using discrete Fourier transformation (DFT). The excitation and response signals generated by the rPWM excitation method are characterized by capturing a wide frequency spectrum within a single measurement, over a few fundamental cycles. This excitation method has been implemented both at the low-voltage and medium-voltage levels, with the technical realization of the power electronic circuit differing depending on the voltage level [48]. The frequency-dependent grid impedance $\underline{Z}_{DUT}$ is then calculated according to formula (3) as the difference between the open-circuit voltage $\underline{V}_{DUT}$ and the voltage response $\underline{V}_{exc}$, divided by the excitation current $\underline{I}_{exc}$.

$$\underline{Z}_{\mathrm{NVP}}(f) = \frac{\underline{V}_{\mathrm{DUT}}(f) - \underline{V}_{\mathrm{exc}}(f)}{\underline{I}_{\mathrm{exc}}} \tag{3}$$

The impedance of three-phase or four-phase systems is determined using the method of asynchronous grid excitation. Initially, loop impedances equivalent to the single-phase measurement principle are measured. Conductor impedances and the symmetrical components are subsequently calculated based on a matrix equation system from three independent measurements. This process assumes the time invariance of the DUT during the measurement of loop impedances [49].

4.2 Impedance Spectroscopy of inverters

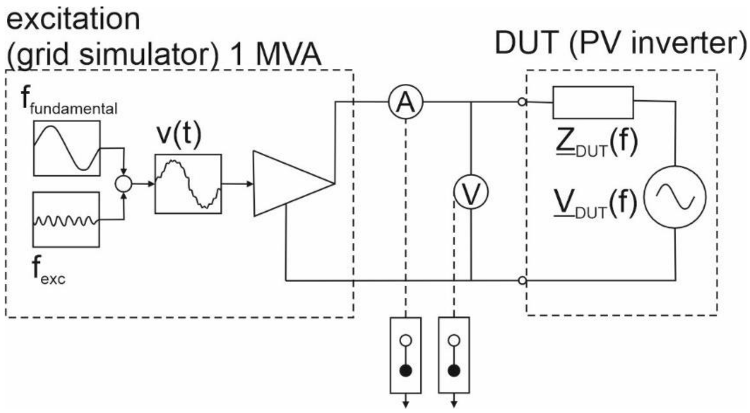

Figure 3. *Schematic representation of the differential impedance spectroscopy according to reference [15].*

The differential impedance spectroscopy method determines the effective frequency-dependent impedance as well as the internal harmonic voltage sources of an inverter [17]. Since the DUT, except for grid-forming inverters, typically requires grid voltage for synchronization, excitation through a load excitation method is not feasible. Most inverters are designed as voltage-following inverters and therefore require grid voltage for synchronization initially. The test bench developed for this purpose is schematically illustrated in Figure 3.

Initially, the inverter is operated on a grid simulation device. Subsequently, the DUT is excited in two independent measurements with a small-signal voltage superimposed on the fundamental grid frequency $f_{\mathrm{fundamental}}$. Throughout these measurements, the frequency of the excitation signal remains constant while either the phase or amplitude is altered. The resulting currents are measured as excitation responses and transformed into the frequency domain.

The impedance $\underline{Z}_{\mathrm{DUT}}$ is then determined as the quotient of the differences between both voltage and current measurements, as per formula (4).

$$\underline{Z}_{\mathrm{DUT}}(f) = \frac{\underline{V}_{\mathrm{exc2}}(f) - \underline{V}_{\mathrm{exc1}}(f)}{\underline{I}_{\mathrm{exc2}}(f) - \underline{I}_{\mathrm{exc1}}(f)} \tag{4}$$

By sweeping through the frequency range, i.e., performing a frequency sweep of the excitation signal up to 10 kHz, a Thevenin equivalent can be calculated sequentially for each excited frequency [17].

The impedances of various inverter types differ significantly. Inverter impedance generally exhibits dependencies on the rated power and filter design. Additionally, the OP, clock frequency, and control parameters also influence the impedance spectrum of the inverters [23, 36]. The internal harmonic voltage sources, as per formula (5), can also be used as a measure for assessing harmonic emission.

$$\underline{V}_{\mathrm{DUT}}(f) = \frac{\underline{V}_{\mathrm{exc1}}(f) \cdot \underline{I}_{\mathrm{exc2}}(f) - \underline{V}_{\mathrm{exc2}}(f) \cdot \underline{I}_{\mathrm{exc1}}(f)}{\underline{I}_{\mathrm{exc2}}(f) - \underline{I}_{\mathrm{exc1}}(f)} \quad (5)$$

The described test bench enables impedance spectroscopy for converters with a power of up to 1 MVA and rated voltages up to 1100 V within a frequency range up to 10 kHz [17].

4.3 Mobile System Impedance Measurement

While the previously mentioned measurement methods and test benches have been tested and validated in multiple measurement campaigns, there is currently no mobile device available for determining system impedances in grid-parallel operation [4, 23, 29].

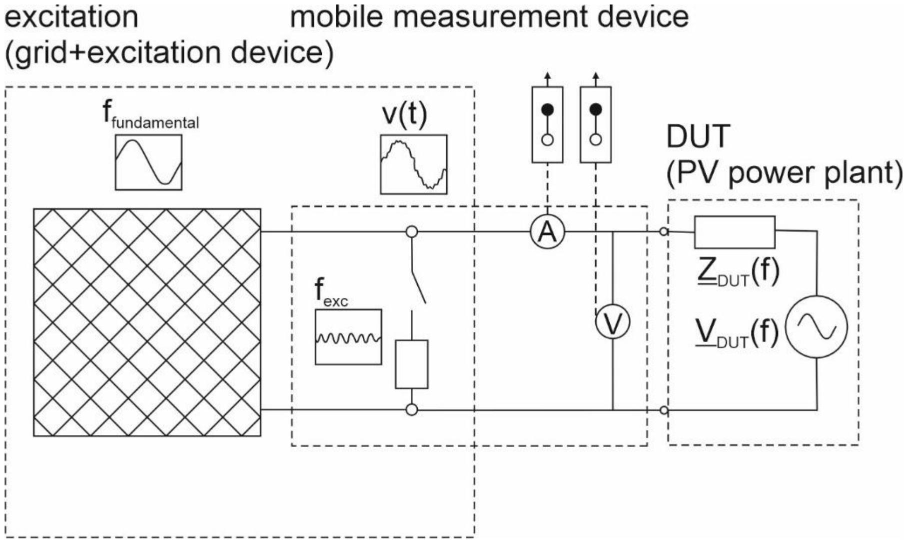

Figure 4. *Schematic representation of the concept for mobile system/plant impedance measurement in the field.*

The requirements for a mobile system impedance measurement in the field differ from those of the existing measurement methods. Initially, at the PCC, the connection point between the GU and the grid, there is a parallel connection between these two systems. By measuring with the grid impedance measurement device at the PCC, the internal behavior of a single-port equivalent to this parallel connection would be characterized. A testing facility with a powerful and highly dynamic AC amplifier, such as the one used for differential impedance spectroscopy, would be too large for mobile field applications.

The concept presented here for mobile system impedance measurement in the field utilizes principles from both methods. A schematic representation of this concept is depicted in Figure 4.To stimulate the DUT, an excitation method based on the described grid impedance measurement technique is used. By shifting the current measurement towards the DUT instead of the excitation unit, the system behavior can be isolated. However, this would result in the weak excitation power at the terminals of the DUT, making precise measurement impossible without further adjustments.

To increase the excitation power, the excitation signal needs to be adjusted. Instead of employing a wideband rPWM excitation, which distributes the excitation power across a very broad spectrum, discrete frequencies are selectively stimulated using a fixed clock rate. By sweeping through the frequency range, i.e., sweeping the clock frequency, the entire spectrum is determined.

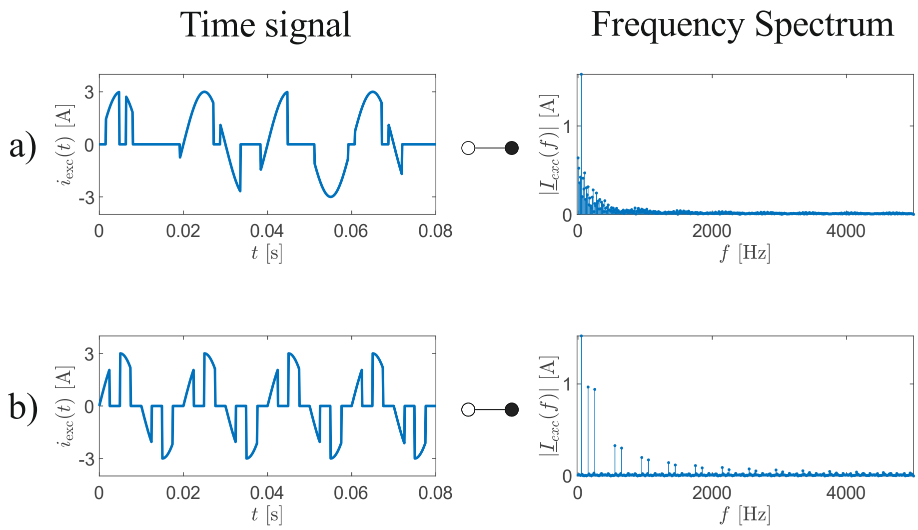

Figure 5. *Excitation signals in the time and frequency domain: a) rPWM excitation, b) discrete excitation.*

Figure 5 presents a comparison between rPWM and discrete excitation in both the time and frequency domains. Additionally, the excitation power can be increased by adjusting the excitation resistance. However, the use of ohmic resistors is technically limited due to the heat losses generated during excitation. Another fundamental modification in the measurement concept involves replacing the ohmic excitation load with a resonant circuit. In an ongoing research project, the new measurement system is being developed as a prototype for the low-voltage level.

5. Summary

To ensure high voltage quality in a power grid largely reliant on renewable power plants coupled with inverters, new evaluation methodologies are required for the grid connection process. Impedance-based assessment approaches are considered promising due to their straightforward principles and demonstrated efficacy in simulations and laboratory trials. However, future considerations must encompass effects known from grid and plant impedance measurements. These encompass site-specific resonance points in the grid impedance, temporal fluctuations, and OP-dependent impedance behavior of inverters. Presently, resonance points in grid impedance and cyclic temporal changes are not accounted for in impedance-based grid connection planning. Additionally, the OP dependency of inverter impedances and their interactions in the parallel operation of a PV park are of practical importance. The development and field testing of such assessment methods are currently pending.

The necessary instruments for implementing a predictive assessment are elucidated in this paper. Employing differential impedance spectroscopy enables the measurement of OP-dependent internal harmonic sources of individual inverters and their input impedance. Additionally, the presented grid impedance measurement device utilizing asynchronous rPWM load excitation has been successfully deployed in medium-voltage applications. However, the measurement-based determination of plant impedances in grid-parallel operation still poses a challenge using these measurement methods. A potential solution concept involves shifting the current measurement towards the DUT to isolate and analyze the behavior of the plant.

Data availability statement

This review paper focuses on summarizing and evaluating the current state of the art. As it is a review article, no primary data collection or analysis has been conducted. The information presented in this paper is based solely on published scientific works, books, and other publicly available sources. All referenced works are listed in the corresponding references. There are no additional data available, as the analysis relies on information already published.

Author contributions

Johannes Schräder: Conceptualization, Investigation, Data curation, Visualization, Writing-original draft, Writing-review&editing, Funding acquisition. Sebastian Kaiser: Conceptualization, Investigation, Data curation, Funding acquisition. Michael Jordan: Conceptualization, Funding acquisition. Detlef Schulz: Funding acquisition, Supervision

Competing interests

The authors declare that they have no competing interests.

Funding

This work was carried out as part of the project „ImaStabil – Impedance Analysis of PV Power Plants to Ensure Stable and Reliable Grid Operation,“ funded by the *Federal Ministry for Economic Affairs and Climate Action* under funding reference number 03EI4060C.

References

[1] J. Gartner, N. A. Müller und B. Engel, „Impact of Harmonics above the 50th Order on the Industrial Grid due to Electric Vehicles in an Employee Parking Lot,“ in *ETG Congress 2023*, Kassel, 2023.

[2] ENTSO-E, „High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters, Technical Report,“ ENTSO-E Technical Group on High Penetration of Power Electronic Interfaced Powser Sources, 2020.

[3] BMWK, „Roadmap Systemstabilität, Fahrplan zur Erreichung eines sicheren und robusten Betriebs des zukünftigen Stromversorgungssystems mit 100 % erneuerbaren Energien,“ Bundesministerium für Wirtschaft und Klimaschutz (BMWK), Berlin, 2023.

[4] Projektkonsortium Netzharmonie, „Optimierte Effizienz und Netzverträglichkeit bei der Integration von Erzeugungsanlagen aus Oberschwingungssicht: Abschlussbericht für das Projekt NetzHarmonie,“ FGW, Berlin, 2019. DOI: 10.2314/KXP:1671617738

[5] J. Schräder, M. F. Meyer, P. Möbius und D. Schulz, „Optimierte Netzanschlussbewertung von Erneuerbaren Energieanlagen durch die Bewertung von Oberschwingungsemissionenmittels zeit- und frequenzabhängiger Netzimpedanzmessungen,“ in *Hamburger Beiträge zum Technischen Klimaschutz 3*, Hamburg, 2021. DOI: 10.24405/13957

[6] F. Ackermann, N. Bihler und S. Rogalla, „Stability prediction and stability enhancement for large-scale PV Power plants,“ in *IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Vancouver, 2016. DOI: 10.1109/PEDG.2016.7527017

[7] J. Enslin und P. Heskes, „Harmonic interaction between a large number of distributed power inverters and the distribution network," in *IEEE Transactions on Power Electronics vol. 4, no.6*, 2004. DOI: 10.1109/TPEL.2004.836615

[8] *DIN EN 50160, Merkmale der Spannung in öffentlichen Elektrizitätsversorgungsnetzen,* 2020.

[9] *VDE AR-N 4110, Technische Regeln für den Anschluss von Kundenanlagen an das Mittelspannungsnetz und deren Betrieb (TAR Mittelspannung),* 2018.

[10] S. Rogalla, F. Ackermann, N. Bihler und O. Stalter, „Source-driven and Resonance-driven Harmonic Interaction between PV Inverters and the Grid," in *IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, Portland, 2016. DOI: 10.1109/PVSC.2016.7749844

[11] K. M. Boroujeni, F. Safargholi und K. Malekian, „Distinction Between "Destructive" and "Constructive" Harmonic Currents to the Voltage Quality," in *TechRxiv. Preprint*, https://doi.org/10.36227/techrxiv.19299479.v1, 2022.

[12] R. J. Bravo, „Solar PV Power Plants Harmonics Impacts," in *IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Denver, 2018. DOI: 10.1109/TDC.2018.8440264

[13] C. Henderson, A. Egea-Alvarez, T. Kneuppel, G. Yang und L. Xu, „Grid Strength Impedance Metric: An Alternative to SCR for Evaluating System Strength in Converter Dominated Systems," in *IEEE Transactions on Power Delivery*, 2023. DOI: 10.1109/TPWRD.2022.3233455

[14] F. Safargholi, K. Malekian und W. Schufft, „"Voltage-Current Ratio Difference" Concept for identifying the dominant harmonic cource," in *Elsevier Electrical Power and Energy Systems*, 2020. DOI: 10.1016/j.ijepes.2020.106147

[15] F. Safargholi, K. M. Boroujeni und F. Santjer, „Voltage-Current Ratio Difference Method: Recommended for IEEE Standard 1547to Determine the Customer Harmonic Contribution," in *IEEE 20th International Conference on Harmonics & Quality of Power (ICHQP)*, Naples, 2022. DOI: 10.1109/ICHQP53011.2022.9808697

[16] J. Sun, „Impedance-Based Stability Criterion for Grid-Connected Inverters," IEEE Transactions on Power Electronics, vol. 26, no. 11, 2011. DOI: 10.1109/TPEL.2011.2136439

[17] S. Rogalla, S. Kaiser, B. Burger und B. Engel, „Determination of the Frequency Dependent Thévenin Equivalent of Inverters Using Differential Impedance Spectroscopy," in *IEEE 11th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Dubrovnik, 2020. DOI: 10.1109/PEDG48541.2020.9244380

[18] Y. Liao und X. Wang, „General Rules of Using Bode Plots for Impedance-Based Stability Analysis," in *IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Padua, 2018. DOI: 10.1109/COMPEL.2018.8460168

[19] N. Cifuentes, M. Sun, R. Gupta und B. C. Pal, „Black-Box Impedance-Based Stability Assessment of Dynamic Interactions Between Converters and Grid," in *IEEE Transactions on Power Systems vol. 37, no. 4*, 2021. DOI: 10.1109/TPWRS.2021.3128812

[20] M. Buchner und K. Rudion, „New Method for Evaluating the Stable Operation of Inverters in the Planning Phase using Impedance-Based Stability Criterion," in *CIRED Conference*, 2021. DOI: 10.1049/icp.2021.1839

[21] S. Shah, P. Koralewicz, V. Gevorgian, H. Liu und J. Fu, „Impedance Methods for Analyzing Stability Impacts of Inverter-Based Resources: Stability Analysis Tools for Modern Power Systems," in *IEEE Electrification Magazine vol. 9, no. 1*, 2021. DOI: 10.1109/MELE.2020.3047166

[22] F. Blaabjerg, R. Teodorescu, M. Liserre und A. Timbus, „Overview of control and grid synchronization for distributed power generation systems," in *IEEE Transaction on Industrial Electronics*, 2006. DOI: 10.1109/TIE.2006.881997

[23] S. Rogalla, S. Kaiser, B. Burger und B. Engel, „Measured Impedance Characteristics of Solar Inverters up to 1 MW," in *10th Solar & Storage Integration Workshop*, 2020. DOI: 10.24406/publica-fhg-409603

[24] B. Wen, D. Boroyevich, R. Burgos, P. Mattavelli und Z. Shen, „D-Q Impedance Specification for Balanced Three-Phase AC Distributed Power System," in *IEEE Applied Power Electronics Conference and Exposition (APEC)*, Charlotte, 2015. DOI: 10.1109/APEC.2015.7104741

[25] C. M. Wildrick, F. C. Lee, B. H. Cho und B. Choi, „A Method of Defining the Load Impedance Specification for A Stable Distributed Power System," in *IEEE Transactions on Power Electronics, vol. 10, no. 3*, 1993. DOI: 10.1109/PESC.1993.472017

[26] R. Luhtala, T. Roinila und T. Messo, „Implementation of Real-Time Impedance-Based Stability Assessment of Grid-Connected Systems Using MIMO-Identification Techniques," in *IEEE Transactions on Industy Applications vol. 54, no. 5* , 2018. DOI: 10.1109/TIA.2018.2826998

[27] T. Messo, R. Luhtala, T. Roinila, D. Yang, X. Wand und F. Blaabjerg, „Real-Time Impedance-Based Stability Assessment of Grid Converter Interactions," in *IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Stanford, 2017. DOI: 10.1109/COMPEL.2017.8013384

[28] M. Li, X. Zhang, Z. Guo, J. Wang, Y. Wang, F. Li und W. Zhao, „The Control Strategy for the Grid-Connected Inverter Through Impedance Reshaping in q-Axis and its Stability Analysis Under a Weak Grid," in *IEEE Journal of Emerging and Selected Topics in Power Electronics vol. 9, no. 3*, 2021. DOI: 10.1109/JESTPE.2020.3024863

[29] Projektkonsortium NEW 4.0, „Abschlussbericht zum SINTEG-Schaufenster New 4.0 Norddeutsche Energiewende 4.0," Hochschule für angewandte Wissenschaften, Hamburg, 2021.

[30] R. Stiegler, S. Schori, K. Scheida, J. Drapela und T. Hanzlik, „Survey of network impedance in the frequency range 2-9 kHz in public low voltage networks in AT/CH/CZ/GE," in *25th International Conference on Electricity Distribution, CIRED 2019*, Madrid, 2019.

[31] Z. Wu, H. Han, J. Lin, S. Xie, Y. Sun, Z. Tang und F. Blaabjerg, „Admittance-Based Stability Analysis of Resistance - Emulating Controlled Grid-Connected Voltage Sources Rectifiers," in *IEEE Transactions on Industrial Electronics vol. 70, no. 10*, 2023. DOI: 10.1109/TIE.2022.3222689

[32] C. Li, M. Molinas, O. B. Fosso, N. Qin und L. Zhu, „A Data-driven Approach to Grid Impedance Identification for Impedance-based Stability Analysis under Different Frequency Ranges," in *IEEE Milan PowerTech*, Milan, 2019. DOI: 10.1109/PTC.2019.8810402

[33] G. Kaatz, M. F. Meyer, F. Grumm, D. Schulz, F. Safargholi, M. Hoven und S. Adloff, „Impedance Frequency Modelling based on Grid Data for the Prediction of Harmonic Voltages," in *IEEE NEIS Conference*, Hamburg, 2018.

[34] Y. Hu, S. Bu, B. Zhou, Y. Liu und C.-W. Fei, „Impedance-Based Oscillatory Stability Analysis of High Power Electronics-Penetrated Power Systems - A Survey," in *IEEE Access vol. 7*, 2019. DOI: 10.1109/ACCESS.2019.2937395

[35] L. Fan, Z. Miao, S. Shah, Y. Cheng, J. Rose, S.-H. Huang, B. Pal, X. Xie, N. Modi, S. Wang und S. Zhu, „Real-Worls 20-Hz IBR Subsynchronous Oscillations: Signatures and Mechanism Analysis," in *IEEE Transactions on Energy Conversion vol. 37, no. 4*, 2022. DOI: 10.1109/TEC.2022.3206795

[36] J. Song, M. Cheah-Mane, E. Prieto-Araujo, J. Amorós und O. Gomis-Bellmunt, „Grid Equivalent Representation of Power Systems With Penetration of Power Electronics," in *IEEE Transactions on Power Delivery*, 2023. DOI: 10.1109/TPWRD.2023.3256440

[37] S. Jiang und G. Konstantinou, „Impedance-Based Stability Analysis: Nodal Admittance or Bus Admittance?," in *IEEE Transactions on Power Systems*, 2023. DOI: 10.1109/TPWRS.2023.3267504

[38] L. Orellana, L. Sainz, E. Prieto-Araujo, M. Cheah-Mané, H. Mehrjerdi und O. Gomis-Bellmunt, „Study of black-box models and participation factors for the Positive-Mode Damping stability criterion," in *International Journal of Electrical Power & Energy Systems vol. 148*, 2023. DOI: 10.1016/j.ijepes.2023.108957

[39] S. Shah, W. Yan, P. Koralewicz, E. Mendiola und V. Gevorgian, „A reversed impedance-based stability criterion for IBR grids," in *21st Wind & Solar Integration Worshop (WIW 2022)* , The Hague, 2022. DOI: 10.1049/icp.2022.2750

[40] E. Kaufhold, J. Meyer, J. Myrzik und P. Schegner, „Framework to assess the stable operation of commercially available single-phase inverters for photovoltaic applications in public low voltage networks," in *21th International Conference on Renewable Energies and Power Quality (ICREPQ`23)*, Madrid, 2023. DOI: 10.24084/repqj21.275

[41] S. Shah, P. Koralewicz, V. Gevorgian und R. Wallan, „Impedance Measurement of Wind Turbines Using a Multimegawatt Grid Simulator," in *18th Wind Integration Workshop*, Dublin, 2019.

[42] S. Shah und L. Parsa, „Impedance-Based Prediction of Distortions Generated by Resonance in Grid-Connected Converters," in *IEEE Transactions on Energy Conversion vol. 34, no. 3*, 2019. DOI: 10.1109/TEC.2019.2904674

[43] S. Shah, P. Koralewicz, V. Gevorgian, R. Wallen, K. Jha, D. Mashtare, R. Burra und L. Parsa, „Large-Signal Impedance-Based Modeling and Mitigation of Resonance of Converter-Grid Systems," in *IEEE Transactions on Sustainable Energy vol. 10, no. 3*, 2019. DOI: 10.1109/TSTE.2019.2903478

[44] S. Shah, P. Koralewicz, V. Gevorgian und R. Wallen, „Sequence Impedance Measurement of Utility-Scare Wind Turbines and Inverters - Reference Frame, Frequency Coupling, and MIMO/SISO Forms," in *IEEE Transactions on Energy Conversion vol. 37, no. 1*, 2021.

[45] R. Stiegler, J. Meyer, P. Schegner und D. Chakravorty, „Measurement of network harmonic impedance in presence of electronic equipment," in *IEEE International Workshop on Applied Measurements for Power Systems (AMPS)*, Aachen, 2015. DOI: 10.1109/AMPS.2015.7312737

[46] M. F. Meyer, G. Kaatz, F. Grumm, M. Plenz und D. Schulz, „Analytical Cable Impedance Modeling Based on Measurement Results," in *NEIS 2019; Conference on Sustainable Energy Supply and Energy Storage Systems*, Hamburg, 2019.

[47] M. F. Meyer, F. Grumm, M. Plenz und D. Schulz, „Determination of a Frequency-Dependent Open Circuit Transformer Model through Grid Impedance Measurements," in *NEIS 2020; Conference on Sustainable Energy Supply and Energy Storage Systems*, Hamburg, 2020.

[48] H. Langkowski, M. Jordan, T. Do und D. Schulz, „Spectral Grid Impedance Identification on Different Voltge Levels - Challenges and Realization," in *IEEE Power & Energy Society General Meeting*, Chicago, 2017. DOI: 10.1109/PESGM.2017.8274683

[49] M. Jordan, F. Grumm, G. Kaatz, M. F. Meyer, H. Wilken und D. Schulz, „Online Network Impedance Spectrometer for the Medium-Voltage Level," in *IEEE International Conference on Enviroment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Palermo, 2018. DOI: 10.1109/EEEIC.2018.8494432