

Real-World Effects of Photovoltaic Systems on Grid Voltage Waveforms

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Abstract

In the course of the energy transition, an increasing number of Photovoltaic (PV) systems are installed in the power grid. By design, they operate differently compared to traditional large power plants. This causes rising concern about their impact on power quality.

In this context, investigations on how PV systems influence the grid voltage distortions lead to different results. Studies report reduced, increased, or unaffected distortions at high PV power feed-in compared to low power. In all these studies, the observed effects are not clearly attributed to the PV system under investigation. Other grid participants (loads and generators) can also change voltage distortions, and their influence is difficult to separate from that of the PV system. Finally, most studies focus on aggregated measures such as Total Harmonic Distortion of the voltage (THD_V) without a detailed spectral analysis. Overall, the actual effect of PV systems on voltage waveform distortions on a detailed spectral level remains unknown. As such, the effects cannot be considered for power quality analysis in the form of simulations. This thesis addresses this gap on a methodological, empirical, and simulative level.

An innovative field measurement method is presented to assess the influence of PV installations on voltage waveform distortions on a detailed spectral level. As such, the measurement and analysis method goes beyond traditional aggregated measures (THD_V) and, in addition, allows for clearly attributing the observed changes in voltage distortions to the system under investigation. The new method applied in several field studies reveals that PV systems have a frequency-sensitive influence on voltage waveform distortions. Individual components are increased or decreased depending on their frequency. The frequency dependence of each investigated PV system is different. The individual characteristic depends on both the connected PV system and the present grid conditions. With additional measurements and investigations, the effects can be attributed to the PV system's impedance characteristic, mainly defined by the grid-side filter of the PV inverter, in relation to the present grid impedance.

To incorporate the observed behavior into simulation studies, this work identifies a suitable modeling approach that is computationally efficient and thus allows a high spectral resolution. Additionally, a dedicated parametrization approach is developed, which allows adapting the model to different PV systems individually. The approach allows acquiring the model parameters of the real-world PV systems while they are connected to the grid and does not need information on the PV system's internal circuit and control.

In conclusion, aggregated values such as THD_V cannot resolve the frequency-dependence of the changes in voltage distortions caused by PV systems. In addition, each PV system in its unique grid has to be characterized individually to account for the diversity in behavior of different systems and grid conditions. This is made possible with the methodology developed in this thesis, and the effect can be incorporated in simulation studies using the modeling approach and parametrization method provided.

Kurzfassung

Im Zuge der Energiewende werden immer mehr Photovoltaik (PV)-Anlagen in das Stromnetz eingebunden. Sie funktionieren grundlegend anders als herkömmliche Großkraftwerke und geben daher Anlass zu Bedenken hinsichtlich ihrer Auswirkungen auf die Versorgungsqualität.

In diesem Zusammenhang führen Untersuchungen ob und wie PV-Anlagen die Netzspannungsverzerrungen beeinflussen zu widersprüchlichen Ergebnissen. Studien berichten von verringerten, erhöhten oder unveränderten Verzerrungen bei hoher PV-Einspeiseleistung im Vergleich zu niedriger PV-Einspeiseleistung. In all diesen Studien lassen sich die beobachteten Effekte nicht eindeutig der untersuchten PV-Anlage zuordnen. Auch andere Netzteilnehmer (Lasten und Erzeuger) können Spannungsverzerrungen verändern, und ihr Einfluss lässt sich nur schwer von dem des PV-Systems trennen. Außerdem konzentrieren sich die meisten Studien auf über die Frequenz aggregierte Größen wie die harmonische Gesamtverzerrung der Spannung (THD_V), ohne eine detaillierte Analyse auf spektraler Ebene zu betrachten. Insgesamt ist der tatsächliche Einfluss von PV-Anlagen auf Spannungsverzerrungen auf detaillierter spektraler Ebene nach wie vor unbekannt. Daher kann dieser Einfluss bei der Analyse der Netzqualität in Simulationen nicht berücksichtigt werden. Diese Arbeit schließt diese Lücke auf methodischer, empirischer und simulativer Ebene.

Dazu wird eine innovative Feldmessmethode vorgestellt, mit der sich der Einfluss von PV-Anlagen auf Spannungsverzerrungen auf einer detaillierten spektralen Ebene bewerten lässt. Die Mess- und Analysemethode geht damit über herkömmliche aggregierte Messgrößen (THD_V) hinaus zu einer vollen Spektralanalyse und ermöglicht außerdem, die beobachteten Veränderungen der Spannungsverzerrungen dem untersuchten System zuzuordnen. Die in mehreren Feldstudien angewandte neue Methode zeigt, dass PV-Anlagen einen frequenzabhängigen Einfluss auf Spannungsverzerrungen haben. Einzelne Verzerrungskomponenten werden je nach ihrer Frequenz verstärkt oder abgeschwächt. Jedes der untersuchten PV-Systeme hat einen anderen Einfluss auf Spannungsverzerrungen. Diese individuellen und frequenzabhängigen Effekte hängen sowohl von der angeschlossenen PV-Anlage als auch von den aktuellen Netzbedingungen ab. Durch zusätzliche Messungen und Untersuchungen lässt sich der Effekt auf die Impedanzcharakteristik der PV-Systeme, welche hauptsächlich durch den netzseitigen Filter des PV-Wechselrichters bestimmt wird, im Verhältnis zur vorliegenden Netzimpedanz zurückführen.

Um das beobachtete Verhalten in simulativen Studien zu integrieren, identifiziert diese Arbeit einen geeigneten Modellierungsansatz, der rechnerisch effizient ist und eine hohe spektrale Auflösung ermöglicht. Zusätzlich wird ein spezieller Parametrisierungsansatz entwickelt, der es erlaubt, das Modell individuell auf verschiedene PV-Systeme abzustimmen. Die Modellparameter der realen PV-Systeme werden dabei ermittelt, während sie an das Netz angeschlossen sind, und Informationen über die interne Schaltung und Steuerung des PV-Systems sind nicht erforderlich.

Die beobachtete frequenzabhängige Änderung von Spannungsverzerrungen bedeutet, dass der Effekt nicht in über mehrere Frequenzen aggregierten Werten wie THD_V erfasst werden kann. Darüber hinaus muss jede PV-Anlage in ihrem Netz individuell charakterisiert werden, um der Vielfalt im Verhalten verschiedener Anlagen und Netzbedingungen Rechnung zu tragen. Dies wird durch die in dieser Arbeit entwickelte Methodik ermöglicht, und der Einfluss kann mithilfe des vorgestellten Modellierungsansatzes und der Parametrisierungsmethode in Simulationsstudien berücksichtigt werden.

“Questions. Questions that need answering.” [1, 0:31:40]

Danksagung

Die in dieser Dissertation zusammengetragenen Antworten auf wissenschaftliche Fragen wären ohne die Unterstützung, die Anregungen und das Vertrauen vieler Menschen nicht möglich gewesen. Ihnen und euch allen, die mich auf diesem Weg begleitet, meine Arbeit bereichert und mich auch über die Wissenschaft hinaus geprägt haben, möchte ich an dieser Stelle von ganzem Herzen danken.

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Acronyms

AC Alternating Current. 22, 29, 33, 35, 36

AI Artificial Intelligence. 85

ANN Artificial Neural Network. 68

CEST Central European Summer Time. 37

DC Direct Current. 22, 29, 33, 36, 38, 54, 75

DER Distributed Energy Resource. 32

DFT Discrete Fourier Transform. 9, 10, 13

DTU Technical University of Denmark. 31, 33, 46

EDR Electrical Data Recorder. 7, 8, 12, 22, 30–33, 35, 46, 50, 54, 83

EMT Electro-Magnetic Transient. 68

FFT Fast Fourier Transform. 9, 11, 12, 18, 28, 81

GPS Global Positioning System. 7

HW Hammerstein-Wiener. 68

IAI Institute for Automation and applied Informatics. 29, 30, 32, 34

IBR Inverter-Based Resources. 1–3, 63, 65, 81, 82

KIT Karlsruhe Institute for Technology. 7, 29, 30, 34

LCL inductor-capacitor-inductor. 56, 57, 83

MPPT Maximum Power Point Tracking. 2, 23, 24

NOCT Normal Operating Cell Temperature. 30

PCC Point of Common Coupling. 56

PLL Phase Locked Loop. 1

PPS Pulse Per Second. 7, 8

PV Photovoltaic. i, iii, 1–5, 7, 20–60, 62–65, 67–85, 105–114

RMS Root Mean Square. 46, 68

STC Standard Test Conditions. 30

SYSLAB Energy System Integration Lab. 31–33, 46–49, 83

THD_V Total Harmonic Distortion of the voltage. i, iii, 2, 3, 7, 58, 81

THD Total Harmonic Distortion. 1, 2, 4, 27, 45, 58

UTC Universal Time Coordinated. 39, 42, 60

1 Introduction

The energy transition towards climate neutrality is one of the most challenging and rewarding developments of our time. There is a need for substantial financial investments and lifestyle changes, but the result will be a green, sustainable future. One of the major changes is the shift from fossil-fuel-based primary energy generation to renewable sources. Solar power plants will make up a large amount of renewable generation in Germany. This technology is inverter-based; it relies on many small power electronics installations instead of the huge rotating generator of traditional power plants.

Research is one cornerstone of the energy transition. By increasing the efficiency of devices, evaluating the huge variety of scenarios, and predicting future challenges to provide timely solutions, it is the foundation that makes the transition possible and economically viable in the first place. There is a multitude of different research questions under investigation. For example, researchers perform power quality and load flow analysis on large models with complex topologies close to that of the real grid to investigate the overall robustness of the power grid. They cannot include every grid-connected device in the greatest detail, down to individual switches and non-idealities, simply due to the limitation of computational resources. On the other hand, researchers interested in optimizing the efficiency of individual converters employ detailed and high-quality laboratory setups and device models, and maintain detailed knowledge and control over the overall internal aspects of the systems under investigation. However, the ever-changing, complex, and unknown characteristics of the real-world grid are out of their reach and, thus, are not included in the investigations. In other words, research itself faces the same challenge as the complex power grid: Many different fields of study and research foci investigating various aspects of the energy system have to come together to provide answers for the entire system as a whole. This work focuses on PV systems connected to the real power grid and investigates them as a one joint system. As a first step, the following section gives an overview of the available literature on the topic and identifies remaining research gaps.

1.1 State of the Art and Research Gap

Ideally, the periodic power grid voltage would be a pure sinusoid with the fundamental grid frequency (50 Hz in the Central European (CE) synchronous grid). In reality, due to non-linear current draws or feed-ins by loads and generators, the voltage is distorted away from an ideal sine. In the frequency domain, such a distorted waveform is described as a superposition of the dominant fundamental frequency and various distortions at other frequencies. Different distortion categories can be differentiated, depending on their frequency: Harmonic, interharmonic, subharmonic, and supraharmmonic components. Harmonic distortions are defined as integer multiples of the fundamental 50 Hz up to 4000 Hz [2]. They are often aggregated into the Total Harmonic Distortion (THD), an overall estimate of the waveform distortion without any frequency resolution. So-called interharmonics are non-integer multiples of the fundamental frequency [2]. Sub-harmonics lie below 50 Hz. Supraharmonics refer to all higher frequencies above 4000 Hz [3, 4]. Distortions can negatively impact the day-to-day operation of the power grid. For example, they can interfere with control and protection, excite resonances and sub-synchronous oscillations, saturate transformers, reduce the lifetime of induction motors, cause flicker, or interfere with Phase Locked Loop (PLL) control systems [5, 6].

More extreme distortion-related incidents are also possible: For example, entire PV systems were reported to shut down due to increasingly large distortions [7, 8, 9, 10, 11, 12]. These incidents include a large variety of observed distortion frequencies like 420 Hz (7th harmonic in 60 Hz system), 780 Hz (13th harmonic), 2370 Hz, and 20 Hz [7]. They raise the critical question of how distortions are generated and how they can be mitigated. PV systems, as an Inverter-Based Resources (IBR), influence

distortions at many frequencies due to their inherent working principle. In contrast to rotating machines, they approximate a sinusoidal voltage or current output using switching operations and flattening hardware filters. It is known that the internal switching actions cause supraharmonics [4], while the Maximum Power Point Tracking (MPPT) of inverters contributes to interharmonics [5]. Naturally, other non-linear loads and generators besides PV systems also participate in the formation of waveform distortions, for example, other IBR such as battery storage systems. However, this thesis focuses its investigations on PV systems as a prominent, widely spread, and continuously growing representative of IBR in the power grid.

Reviewing the current literature reveals that waveform distortions associated with PV systems are the center of interest for many researchers. The list of research questions raised in this context is long and can be clustered into three groups referring to the environment in which the systems are investigated: Simulative studies, laboratory tests, and field measurements. In this context, the distortions of the inverter current waveform that the PV system feeds into the grid are well researched. Several dependencies are well-known and thoroughly investigated: The inverter current quality is reduced at low PV power outputs [13, 14, 15]. Already present grid voltage distortions increase current distortions at the same frequency, known as the auto-sensitivity effect [13, 14, 16, 17, 18, 19, 20]. Frequency coupling is also possible and causes so-called mirror frequencies in the inverter current [21, 22]. In contrast, observations on whether and how the distorted inverter current subsequently affects the grid voltage waveform are less abundant. An overview of these few studies is given in the following. They all performed field measurements on PV systems and evaluated voltage waveform distortions. There are two practical reasons for focusing on field measurements: First, a majority of PV systems are installed in the field and have to be characterized directly there, because they cannot be packed up and transported to a laboratory without immense effort and monetary investment. Second, both the grid and the PV system are complex systems with limited information available on them, making it impossible to recreate them in their entirety in laboratory setups or simulation models.

Acero et al. (2020) [23] present data measured at a PV system in Peru. They observe that THD_V is reduced whenever the system's power feed-in is small. In contrast, Al-Majidi et al. (2021) [24] report larger overall voltage distortion during small PV power feed-in, by investigating voltage distortions at a PV system in Great Britain on two different days [24]. They observe that the THD_V is a little smaller on the sunny day compared to the cloudy day. As such, they agree with Alawasa and Al-Odienat (2019) [25] who also observe increased THD_V at lower PV power feed-in. As reported by Adebisi and Davidson (2023) [26] and Seme et al. (2017) [27], it is also possible that the voltage distortion does not change for different PV powers. For example, the THD_V is constant over the day, even though the inverter power follows a typical day profile [26].

These contradictory findings highlight the need for deeper investigations. Many of the above studies focus on THD in relation to PV power levels [25, 26, 27]. THD_V , as a collective parameter, may not sufficiently capture underlying processes. Sometimes the waveform distortions of the inverter current are indeed investigated in the frequency domain in great detail as the main focus of the analysis, while evaluation of individual voltage harmonics is missing [23]. Only some studies extend their analysis to individual harmonic voltage components [28, 29, 30] or at least all odd-order harmonics [14, 19, 31]. Few studies go beyond harmonics to analyze full spectra with high frequency resolution [24, 32], and the importance of maintaining a spectral view is recognized [33].

All the above studies compare voltage distortions during different inverter power outputs. However, based on these comparisons, the PV system cannot be directly identified as the root cause of the voltage waveform alterations. The connected grid also includes other nonlinear loads and generators. These might follow a similar temporal evolution as the PV power and can also affect the voltage distortion. Ahmed et al. (2017) [34] apply a different approach and compare power quality parameters before and after a PV system was installed. They report that after the installation of the PV system at their institute in Egypt, the THD_V decreased. Barbu et al. (2013) [35] also report a reduced THD_V during active PV system, by comparing daytime with nighttime data. These approaches link the voltage distortion changes more directly to the investigated PV system. Nevertheless, in the real-world grid and its many unknown and time-varying loads and generators, each contributing their own behavior, other influencing factors (other nonlinear loads/generators) cannot be excluded. In addition, these studies again focus on overall distortion metrics and lack a detailed spectral analysis. While individual harmonics are calculated, their dependence on the system's presence is not analyzed.

In summary, the actual influence that PV systems have on voltage waveform distortions in the real-world grid remains unclear. Different studies report increased, decreased, or unaffected THD_V at higher PV power output. Reduced THD_V is reported when the PV system is operational compared to the grid without the system installed/running. All the field studies lack spectral depth; instead, they focus on total distortion values. In addition, the changes in THD_V cannot be attributed to the respective PV systems under investigation, as other influencing factors are not conclusively excluded.

1.2 Research Questions and Contributions

In the future inverter-dominated grid, knowledge about the influence of IBR on voltage distortions is crucial. However, the reviewed literature does not provide conclusive reports on how PV systems directly influence voltage distortion in the field. Based on the identified gap, this thesis addresses the following main research question:

How do photovoltaic systems affect the grid voltage waveform in the field on a detailed spectral level?

For a successful response, the question is approached on three levels: methodological, empirical, and in simulation.

Due to the complexity of the public distribution grid, the influence of the system under investigation is difficult to isolate from that of other nonlinear loads and generators (which also influence voltage distortions). In other words, it is difficult to be certain that the PV system is responsible for the observed effects. In addition, investigating PV systems directly in the field poses several requirements. Any measurements cannot have a lasting negative impact on the investigated system or neighboring grid infrastructure. They should also be easily applicable to a high number of different systems to capture their individual characteristic influence on voltage distortions. Finally, as already mentioned, traditionally popular total distortion parameters lack spectral depth and cannot detect frequency-sensitive effects. So the acquired data must allow an analysis in high spectral resolution. These requirements foreshadow a complex answer to the first methodological question:

1. How can the influence of a PV system be identified and separated from that of other loads and generators?

This thesis contributes an innovative field measurement method that allows for clearly attributing observed dependencies to the system under investigation. It is fast and easy to implement in an arbitrary system in the field and comes with a completely non-intrusive alternative if required. The high resolution of the underlying voltage measurements allows a detailed spectral analysis.

With the developed method, the actual effect of PV systems on voltage distortions can finally be characterized in high spectral resolution. A multitude of PV systems is installed in the public distribution grid. They cover a huge variety of power ratings, inverter manufacturers, locations, and other parameters. No system is the same as the next, and each might have a different influence on voltage distortions. A variety of systems should be characterized and compared to allow for an overall assessment of how systems in general influence distortions. Applying the new method in various field measurements will enable answering the following second sub-question:

2. How do different in-field PV systems change voltage distortions on a spectral level?

The characterization of three different commercial PV systems reveals that the influence of the systems on voltage distortions is frequency sensitive, installation-specific, and depends on the connected grid. Each system has an individual characteristic and can increase distortions in one frequency region while reducing them at other frequencies. In addition, the same system can have very different influences when connected to different grid configurations. Extended root-cause studies attribute the observed dependencies to an alteration of the overall grid impedance due to the addition of the grid-side hardware filter of the PV inverter.

The observed complex and system-specific character of the PV system needs to be made available for studies that investigate distortion scenarios in future power grids. This equals transferring the effects to the simulation domain in the form of a model. The model must allow a high spectral resolution and be able to incorporate the complex frequency

dependencies. Simulation studies rely on parameters that map the model behavior to the real-world system and allow a correct prediction of system behavior. As limited information is available on commercial PV systems and the connected grid, the model adaptation to a specific system must be possible with only the available measured data. Finally, to be usable in large grid studies limited by computing resources, the developed model must run computationally efficiently. Overall, to create impact from the empirical results, the following research question is raised:

3. How can the change in voltage distortions due to the PV system be represented in models?

This thesis identifies frequency-domain, impedance-based models as the appropriate modeling approach to capture the frequency-dependent change of voltage distortions due to a connected PV system. To adapt the model to a specific system, a new extraction method for the impedance of the grid-following PV system is presented, which does not require isolated measurements of the system without the grid. Due to the frequency-domain nature of the model, it allows a high spectral resolution while being computationally efficient.

1.3 Thesis Outline

The present introduction has reviewed the state of research and identified remaining research gaps. Based on these gaps, three research questions are formulated, addressing methodological, empirical, and modeling challenges. Each of these three research questions is systematically addressed in a separate chapter in this thesis.

Chapter 2 develops the methodological foundation required to isolate and quantify the effect of a PV system on voltage waveform distortions in real field conditions. The central contribution of this chapter is an innovative measurement method designed to address research question number one (compare list of research questions in Section 1.2). To achieve this, the chapter first establishes the technical basis by introducing the measurement equipment (Section 2.1). It then develops and validates a spectral analysis framework (Section 2.2 and Section 2.3) tailored to the required high-resolution distortion analysis. Building on these elements, a generalized measurement procedure is formulated (Section 2.4). The method is explicitly designed to overcome the difficulty of separating the influence of the system under investigation from that of surrounding loads and generators and thus enables the attribution of observed distortion effects to the PV system itself. The resulting method is not limited to a specific setup but is applicable to arbitrary systems in real-world grid environments.

Chapter 3 provides the empirical resolution of the second research question by applying the developed method to three different commercial PV systems in the field. The chapter follows a structured approach: after introducing the investigated systems and their grid environments (Section 3.1), the measurement method is systematically applied, and the results are evaluated (Section 3.2 and Section 3.3). The results demonstrate that the influence of PV systems on voltage distortions is inherently frequency-dependent, installation-specific, and strongly influenced by the surrounding grid configuration. This directly shows that aggregated metrics such as THD are insufficient to describe these effects. Instead, a detailed spectral perspective is required, and system behavior cannot be generalized across installations. The chapter also conducts targeted root-cause investigations (Section 3.4). By combining additional impedance measurements with extended voltage and current analyses, the observed behavior is attributed to changes in the overall grid impedance, primarily caused by the grid-side hardware filter of the inverter. This step completes the empirical understanding by linking measured effects to their physical origin.

Chapter 4 addresses the third research question by translating the empirical insights into a simulation-based modeling framework. From the range of available modeling approaches for grid-connected PV systems, an impedance-based frequency-domain model is selected as the most suitable representation of the observed phenomena (Section 4.1). Also, a key contribution of this chapter is the development of a parametrization strategy derived from field measurements (Section 4.2). In particular, a practical method is introduced to determine the impedance characteristics of a grid-following PV system without requiring direct or isolated measurements that are infeasible in practice (Subsection 4.2.2). Using this parametrization, the model successfully reproduces the frequency-dependent influence of the PV systems on voltage distortions observed in the field (Subsection 4.2.3).

This demonstrates that the proposed modeling approach not only captures the relevant physical mechanisms but also provides a consistent representation across measurement and simulation domains.

Chapter 5 concludes the thesis by summarizing the methodological, empirical, and modeling contributions. It reflects on their implications in the broader context of power quality assessment and grid integration of PV systems, and outlines directions for future research. Additional analyses, extended datasets, and supplementary investigations are provided in the appendix (Appendix A) to support and complement the main findings without interrupting the central line of argumentation.

2 New Field-Measurement Method for Photovoltaic Inverters

Section 1.1 identified several gaps in available in-field investigations on PV system and their effects on voltage waveform distortions: PV systems are reported to increase, reduce, or not affect voltage distortions. These inconsistent findings might be related to the lack of in-depth spectral analysis because investigations rely on total distortion values such as THD_V . In addition, the effects described in prior works are not clearly attributed to the PV system under investigation because the influence of other loads and generators is not excluded. This chapter presents a new method to investigate PV systems in-field in high spectral resolution. It is especially adapted to the requirements of real-world field measurements and clearly attributes the observed characteristics to the system under investigation by excluding the potential influence of other grid components.

First, Section 2.1 introduces the voltage and current measurement device applied throughout this thesis. Then, Section 2.2 presents the developed spectral analysis algorithm that is specifically tailored to the requirements of voltage and current waveforms and to the present data format and research focus. The analysis routine is evaluated in Section 2.3 using a specifically developed validation framework and is found to be well-suited for detecting changes in voltage distortion amplitudes in high-frequency resolution. Finally, Section 2.4 presents the new and innovative field-measurement method necessary to quantify the influence of PV systems on voltage waveform distortions. Both a more robust methodological approach and a less intrusive alternative are presented to allow flexible application at different systems, depending on the degree of access and manipulation they allow.

An exemplary application of the method to a first system under investigation is also published in [O2]. Here, the fundamental working principle as well as the underlying data analysis are evaluated in more detail, and the method description remains generic to be applicable to an arbitrary system.

2.1 Measurement Equipment: Electrical Data Recorder

All voltage and current measurements in this thesis were acquired using the Electrical Data Recorder (EDR). The EDR is designed to record three-phase electrical signals in the public power grid. It is the result of a continuous development process at the Institute of Automation and applied Informatics at the Karlsruhe Institute for Technology (KIT) [36, 37, 38, 39, 40, 41, 42, 43, O3, 44, O4, 45]. This section gives an overview of the device's functionality and data acquisition. Presented information is based on [42, 45]. Additional functionalities and details can be found there.

The EDR has two major components: The measurement hardware and the data processing software. On the hardware side, the analog front end conditions the signal for acquisition. This includes an anti-aliasing Butterworth filter of third order. The filter shows a flat range up to 14 kHz. An eight-channel 16-bit data acquisition card captures and digitizes voltage and current signals at a sampling rate of 25 kHz. The software is installed on a commercial laptop. It controls measurement settings like the start and end of acquisition. In addition, it receives, processes, stores, and forwards the digital data. This includes the evaluation of time information: Time stamps are obtained from the synchronously captured Pulse Per Second (PPS) signal received by a Global Positioning System (GPS) receiver. PPS-based synchronization allows temporal alignment of measurements at different locations.

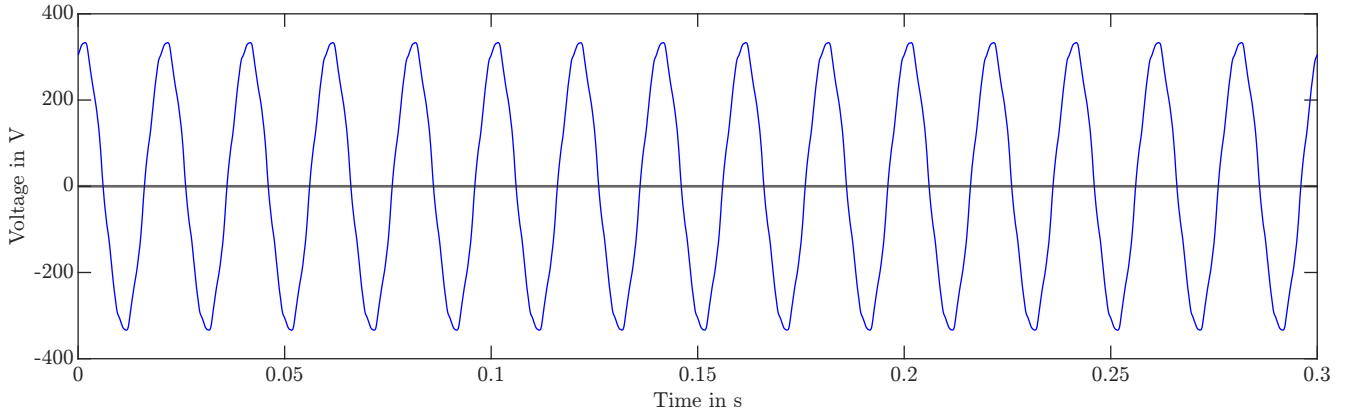


Figure 2.1: Exemplary snippet of grid voltage waveform follows a sine wave with a frequency of 50 Hz but also contains distortions.

The raw waveform data is stored in XML-coded files, including metadata such as timestamps, location data, and measurement parameters. Each second of the high-resolution time-series (data from one PPS to the next) is encoded separately as a 16-bit base64 stream and stored in a separate XML section together with the metadata. One XML data file is created per minute. It is uploaded to a database at the Karlsruhe Institute of Technology (KIT). Next to the raw waveform storage, different feature parameters are calculated directly by the device. For example, the fundamental frequency is extracted based on a zero-crossing estimation algorithm, and the amplitude and effective values of voltages and currents, as well as power estimates, are calculated.

The EDR is the perfect device for the research in this thesis: It is designed to allow continuous capture and storage of raw data (voltages and currents) in 25 kHz resolution. This allows high flexibility in the analysis of waveforms at the cost of the large storage capacity required. In contrast, commercial Phasor Measurement Units (PMUs) often only report aggregated feature data at much smaller sampling rates. This feature data includes, for example, effective voltage measurements, fundamental frequency estimates, or total distortion values. Such low-resolution feature parameters, even though also provided by the EDR, are not considered in this work.

The voltage is measured with a high accuracy of more than 0.1 % [42]. The time stamps assigned to the data points have microsecond accuracy. Due to the use of Rogowski coils for current measurements, the accuracy of current values reaches 1 % [42]. The accuracy depends on the position of the coil relative to the wire under investigation [46]. External sources that generate interfering signals introduce additional errors. To increase the amplitude accuracy, [45] suggests a calibration on-site.

This thesis focuses on distortions in the grid voltage. Explicitly, the high-resolution voltage data stored in the XML files is analyzed for present distortions on the waveform using the analysis routine described in the following section. Even though the current is also continuously captured, only one short snippet of the current measurements is analyzed for its distortion composition for an exemplary comparison with the voltage distortion. Due to the focus on voltage measurements, no on-site calibration for current measurements was performed, and current amplitudes have to be interpreted with caution.

2.2 Data Analysis: Extraction of Spectral Components from Voltage Time-Series

The previous section presented a device that captures voltage and current time-series in 25 kHz resolution. An exemplary snippet of voltage measurements is shown in Figure 2.1. The voltage is close to an ideal sine with a frequency of 50 Hz. However, especially visible at the highest and lowest points of the signal, deviations from the ideal signal are visible. This work aims to investigate these distortions in high spectral resolution. They can be extracted from a time signal using the well-established method of Fourier transformation [47, 48]. This section presents the analysis routine used in this work to extract spectral information from voltage and current measurements. It is based on a Fourier analysis, but the data handling

and preprocessing are especially designed to work well for the characteristics of voltage and current signals. This section first presents the challenges associated with Discrete Fourier Transform (DFT) in Subsection 2.2.1. Then, Subsection 2.2.2 describes in detail how the data analysis is implemented in MATLAB.

2.2.1 Fundamentals: Challenges associated with Discrete Fourier Transform

Any time-domain signal can be transformed to the frequency domain using the Fourier transform. The specific characteristic of the time-domain signal determines which type of transformation needs to be used. Sampled signals are always discrete and finite. They are transformed into a discrete and finite frequency spectrum using the DFT [49]: A sequence of measured data points $x(n)$ with length N can be represented by a series of complex exponential signals of length N [2, 49, 50]:

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k) e^{jk \frac{2\pi}{N} n}, \quad n = 0, \dots, N-1; \quad k = 0, \dots, N-1. \quad (2.1)$$

The complex DFT coefficients $X(k)$ can be expressed by their amplitude c_k and phase angle φ_k : $X(k) = c_k e^{j\varphi_k}$. This variable naming follows the definitions in [2] to allow comparability with other works. The k -th spectral component lies at the frequency $f_{C,k} = k \frac{f_s}{N}$, with the sample rate f_s of the time-domain signal. In case of electrical signals, it is also possible to use the effective value $Y_{C,k} = \frac{c_k}{\sqrt{2}}$ instead of the amplitude c_k [2].

While easy to perform, the DFT of long and high-resolution signals (large N) requires high computational cost. The problem has a complexity of $O(N^2)$ [48]. The Fast Fourier Transform (FFT) first introduced by Cooley and Tukey (1965) [51] reduces the complexity to a minimum of $O(N \log N)$ [48]. However, the fast algorithm only works on data snippets with a length that equals a power of two: $N = 2^m$, $m \in \mathbb{N}$.

The Fourier window is the time interval of the signal that is transformed to the frequency domain. Its width Δt equals the period duration of the smallest frequency resolvable by the transformation. This also determines the frequency resolution of the resulting spectrum, as each bin is a multiple of this smallest representable frequency. As an example, a Fourier window of 1 s results in a frequency spectrum with a resolution of 1 Hz. DIN EN 50160 (2020) [52] suggests to analyze consecutive 200 ms intervals resulting in a frequency resolution of 5 Hz.

Due to its discrete nature in both the time and the frequency domains, the DFT poses several challenges that must be taken into account when interpreting spectral data [49, S1].

- According to the Nyquist-Shannon sampling theorem, a signal requires the sampling frequency to be double the highest frequency contained in the signal. Only then can the signal be correctly reconstructed from the frequency spectrum. In other words, the Nyquist frequency (half the sampling frequency $f_{Ny} = \frac{f_s}{2}$) is the highest frequency that can be resolved by the DFT [53]. If the time domain signal contains frequencies higher than f_{Ny} , these are mirrored to and represented by a smaller frequency component. This folding of frequencies is known as aliasing [49]. Aliasing can be reduced by filtering a time-domain signal before transformation to eliminate frequencies above the Nyquist frequency.
- The DFT analyses a finite interval of data (Fourier window) but assumes this signal to extend periodically [49]. If a non-integer number of signal periods is contained in the Fourier window, discontinuities between the start and end of the signal occur. These discontinuities are represented by multiple frequencies in the spectrum (as opposed to just one component at the signal frequency). Such a spreading of signal components into multiple frequencies is called leakage. Leakage can be reduced by choosing an appropriate signal interval containing full periods of all frequencies present in the signal. However, if a large variety and multitude of frequencies are contained in a signal, an interval that fits all is often impossible to find. An alternative approach to reducing leakage is the multiplication of window functions onto the signal before transformation. The window function forces continuity at the start and end of the Fourier window

¹ Please note, due to the sampling theorem discussed later, the highest resolved frequency is $\frac{f_s}{2}$, so k only runs from 0 to $\frac{N}{2}$ here.

by reducing the signal amplitude to zero. The functional dependence inside the Fourier window can look different, depending on the chosen window function. Window functions reduce leakage at the cost of increased local dispersion (spreading of components into several close-neighbor bins). This reduces spectral resolution and amplitude accuracy. Amplitude accuracy can be restored after transformation using correction factors appropriate for the window function used.

- The Picked-Fence Effect describes how the discretization in the frequency domain influences the signal representation [49]. If a signal contains a component at 12.47 Hz but the frequency spectrum has a frequency resolution of 1 Hz and bins only at 12 Hz and 13 Hz the amplitudes in these bins will be smaller than the amplitude at the actual peak frequency. The discretization looks at the actual continuous frequency representation through a picked fence. Zero-padding can be used to artificially increase the frequency resolution (filling up the Fourier window with zeros). This increases the spectral resolution but does not contain additional information.
- Finally, the transformation requires the signal to be stationary over the Fourier window. If the signal contains non-periodic changes over time, a shorter transformation interval should be chosen.

2.2.2 Implementation: Specialized Pre-Processing to Reduce Leakage

Based on the fundamental concepts and challenges associated with DFT, the following parameters have to be carefully selected for each specific application: Anti-aliasing filter, the analyzed time interval (Fourier window Δt), the sample rate f_S , window function, and post-processing of frequency-domain data.

In this thesis, large amounts of current and voltage data from the public distribution grid are analyzed. These signals often show a large variety of frequency components. The primary component is the fundamental frequency around 50 Hz in the central European grid. In addition, nonlinear loads and generators cause a variety of distortions with much smaller amplitudes at multiple other frequencies that are superimposed. These include harmonics at integer multiples of the fundamental frequency and interharmonics that are non-integer multiples of 50 Hz. The distortions are most prominent in the frequencies below 4 kHz. Grid voltages and currents change with time, both concerning the fundamental frequency and the distortion composition.

The research questions focus on changes in distortion composition from one point in time to the next over a large range of frequencies. Absolute amplitude accuracy and individual peak position of components (frequency resolution) are a secondary concern. The large amount of data requires compromises in the analysis to keep the computational cost manageable. This thesis provides a spectral analysis optimized for analyzing these types of signals and the research goal. The analysis is implemented in MATLAB [54].

Waveform data from t_{start} to t_{end} is processed in the following steps:

1. **Data import** The entire XML-formatted data file is imported (compare Section 2.1 for information on the measured data format). Specifically, each one-second string of base64-encoded voltage or current samples is read and decoded one after the other and joined together to one continuous time series. The corresponding time stamps are assigned to the individual samples based on the time and sample rate information in the metadata.
2. **No additional aliasing filter is required:** The measurement device already includes alias filtering (compare 2.1). In addition, voltages and currents are primarily distorted by frequencies below 4 kHz. No significant signal components above this frequency are expected that could cause aliasing.
3. **Fourier window Δt based on zero-crossings to reduce leakage from the fundamental frequency component:** In principle, time-signals of arbitrary length can be analyzed. However, if the signal composition changes with time, the Fourier window has to be chosen shorter than the signal's dynamic. To account for different dynamics, this thesis considers three different time resolutions: 1 s of data, a 200 ms window, and a 100 ms window. To avoid leakage, the window Δt has to contain an integer number of periods of the fundamental frequency. To do so, the Fourier window

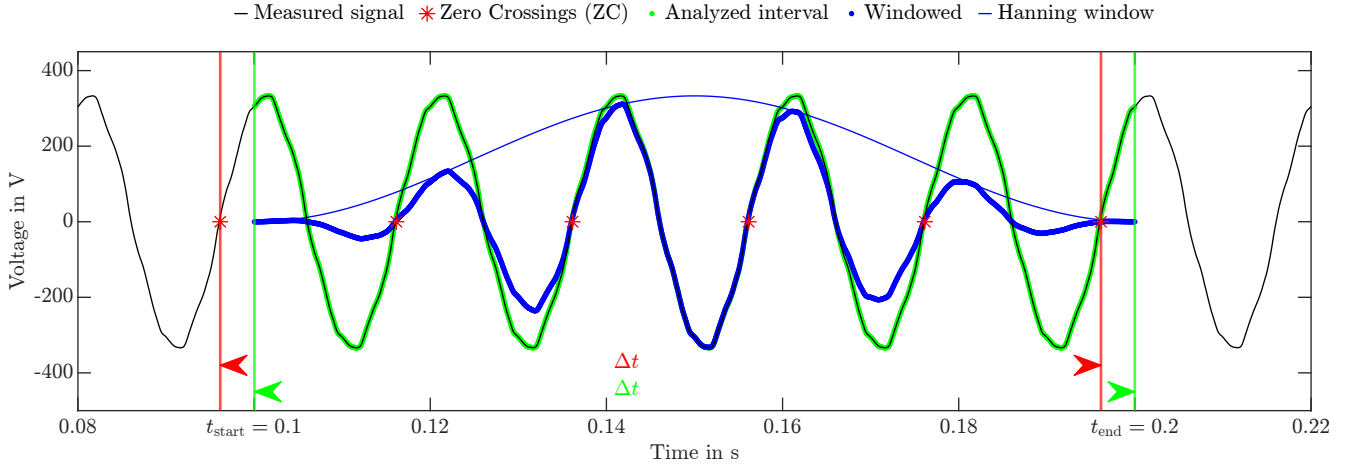


Figure 2.2: Time-signal preparation before Fourier transformation reduces leakage in the spectrum.

is chosen based on positive zero crossings (zero crossings with positive slope) of the voltage time-series. The first zero crossing before t_{start} and the last zero crossing before t_{end} are identified. The duration Δt between the first and last zero crossing contains full periods of the fundamental frequency (e.g., 5 periods in case of a 50 Hz signal and 100 ms interval). The window Δt only equals a duration of exactly 1 s, 200 ms, or 100 ms, if the frequency is exactly 50 Hz. However, most of the time, the actual grid frequency differs from 50 Hz by a few mHz. The final Fourier window of width Δt , starting at t_{start} , contains full periods of the fundamental frequency.

4. **Resampling to balance Nyquist frequency and computational cost:** The measured data is available at a sample rate of 25 kHz. However, to reduce the computational cost for the transformation, the signal is resampled to a smaller sampling rate. Firstly, the final number of samples per Fourier window should be a power of two 2^m , $m \in \mathbb{N}$ to exploit the faster FFT algorithm. Secondly, the sample rate has to be twice the highest signal component (Nyquist). This work focuses on distortions up to 4 kHz. Here, the data is resampled to 2^{13} points in case of 1 s interval, 2^{11} for 200 ms, and 2^{10} for 100 ms interval. This leads to effective sample rates of roughly 8.1 kHz (1 s Fourier window) and 10.2 kHz (200 ms and 100 ms Fourier window). The resulting Nyquist frequencies are half these sample rates and are thus above the highest frequency of interest.
5. **Hanning window function to reduce leakage from components other than fundamental:** This work multiplies the Hanning window by the data before transformation to ensure high-frequency accuracy by reducing wide-range leakage at the price of increased close-range leakage [55].
6. **Transformation to frequency domain using an FFT algorithm:** The prepared data snippet is transformed to the frequency domain using a FFT algorithm. From the resulting complex spectrum, the absolute positive frequency magnitudes c_k , labeled $\mathcal{V}_k$ in the case of voltages and $\mathcal{I}_k$ for currents, are extracted for further evaluation (compare documentation on the `fft()` function by MATLAB [56]). The phase angles φ_k in Equation 2.1 are the angles of the complex spectral components, wrapped to the interval $[0, 2\pi]$.
7. **Correction factor to account for Hanning window usage.** A Hanning window correction factor of two [57] is multiplied to all components.

Figure 2.2 summarizes the data preparation before transformation to the frequency domain, exemplarily, for a 100 ms interval of raw data for easier visualization. First, the zero-crossings of the signal are identified. Based on these, a duration of Δt is chosen that contains full fundamental periods of 50 Hz. The final Fourier window of the same duration starts at t_{start} . With the Hanning window, the signal amplitudes are zero at the start and end of the interval. Finally, the windowed signal (blue) is fed into the FFT.

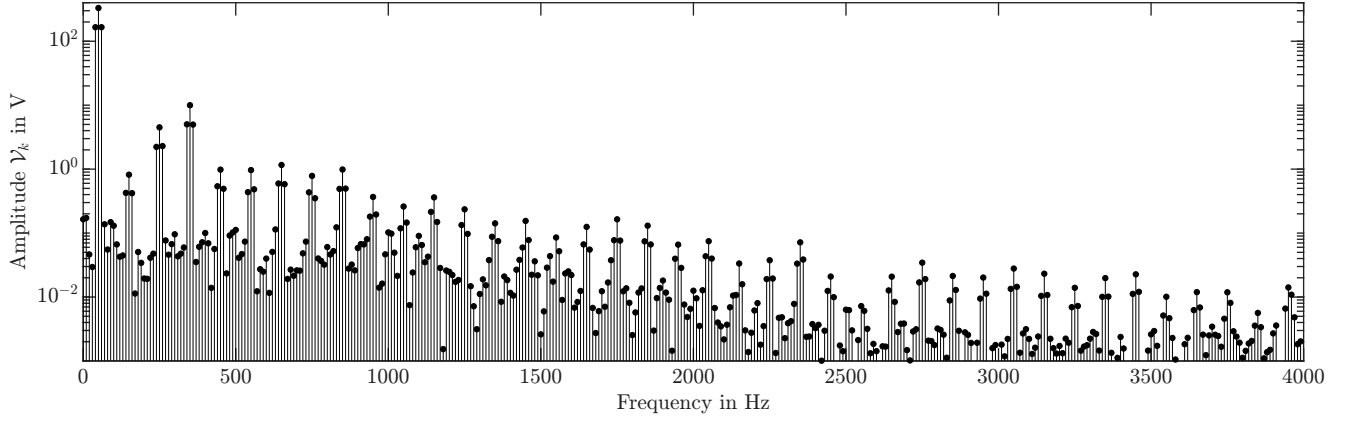


Figure 2.3: Exemplary voltage spectrum in logarithmic scaling.

The resulting spectrum is visualized in Figure 2.3 up to 4 kHz. The frequency resolution of the bins in the spectrum depends on the time window analyzed. Here, based on the 100 ms interval, the frequency resolution is 10 Hz. The y-axis showing the amplitudes/spectral components V_k is scaled logarithmically to allow visualization of the dominant fundamental component at 50 Hz as well as smaller components at other frequencies. Among the distortions, odd multiples of 50 Hz, so-called odd harmonics, have the highest amplitudes, especially orders 5 and 7. All components in-between harmonics are called interharmonics; they have overall smaller amplitudes compared to harmonics. The amplitude of spectral components, both harmonics and interharmonics, reduces with frequency. Distortion amplitudes are smaller at higher frequencies. Frequencies above 4 kHz are not included in Figure 2.3. These components have even smaller amplitudes compared to the highest frequencies included in the figure. Each frequency component with high amplitude contained in the time-signal is represented by three bins in the spectrum. This is due to the Hanning window, which reduces leakage at the cost of increased local dispersion into neighboring bins.

The same spectral analysis is repeated for each consecutive time interval (1 s, 200 ms, and 100 ms), resulting in a time series of spectral components. This work usually analyzes consecutive 1 s intervals of data to make use of the increased frequency resolution.

2.2.3 Summary and Discussion

The extraction of spectral information from real-world measurement data poses several challenges, primarily due to the discrete nature of the transformation from the time to the frequency domain (Subsection 2.2.1). Among the available methods, the Fourier transform is the most widely used approach, as it offers efficient computation and straightforward implementation through established routines. In this work, a tailored data analysis algorithm has been developed to extract voltage and current distortion amplitudes and phase angles as a function of frequency from time-domain measurements obtained with the EDR. The proposed routine, based on the FFT, enables the simultaneous evaluation of all relevant frequency components and is specifically designed for the characteristics of the available dataset.

Several measures are implemented to enhance the accuracy and robustness of the spectral analysis. Spectral leakage is reduced by selecting the Fourier window length such that it contains an integer number of periods of the dominant fundamental frequency at 50 Hz. Additionally, a Hanning window is applied to the signal before transformation to suppress leakage contributions from superimposed frequency components. To ensure computational efficiency, the waveform data are downsampled to a sampling rate twice the highest frequency of interest, thereby minimizing data volume while retaining all relevant spectral information. Furthermore, the analysis routine offers three selectable time resolutions, allowing an appropriate trade-off between temporal and spectral resolution depending on the signal characteristics. The overall data analysis process is streamlined, encompassing data import, preprocessing, quality assurance, and continuous evaluation over long time series.

Despite these strengths, the approach faces certain limitations: The presence of multiple superimposed distortion frequencies leads to complex spectra, making it impossible to simultaneously optimize the Fourier window for all components. Interactions between closely spaced frequency components can occur due to finite resolution and residual leakage. Although the implemented mitigation measures significantly reduce these effects, they cannot eliminate them entirely. In addition, the analysis assumes that the signal remains quasi-stationary within each Fourier window. If the spectral composition changes within this interval, the resulting representation may not accurately reflect the true temporal dynamics. The chosen time resolution of 1 s, 200 ms, or 100 ms therefore defines the maximum dynamics that can be reliably captured. These methodological considerations imply the need for careful validation of the analysis results, particularly with respect to the effectiveness of the implemented leakage reduction strategies. Furthermore, the analysis is restricted to frequencies below the Nyquist limit, with the current implementation covering components up to 4 kHz. The limited frequency range will be taken into account throughout this thesis, and all spectral representations are restricted to below 4 kHz.

At present, the processing is performed sequentially; however, the independent nature of individual Fourier windows would allow for parallelization to further accelerate computation. Future work could additionally extend the spectral range beyond 4 kHz, provided that measurements with sufficiently high sampling rates are available and computational resources permit the processing of the corresponding data volumes. If improved accuracy for individual frequency components becomes necessary, further refinement of the analysis could be achieved through targeted filtering or interpolation techniques to mitigate binning effects. However, such approaches would typically reduce the ability to simultaneously assess the full spectrum, which is a key requirement of the present thesis.

Overall, the developed method provides a streamlined and application-specific framework for spectral analysis of measured voltage and current signals. It is well-suited for the simultaneous evaluation of frequency-dependent distortion characteristics and forms a robust basis for the subsequent analyses presented in this work. Due to the discussed limitation, before the usage of the method, the following section introduces a dedicated validation procedure also developed within this thesis.

2.3 Validation: Developed Spectral Analysis is Well-Suited to Investigate Changes in Distortion Amplitudes

Due to the many challenges associated with DFT and real-world, discrete data identified in Subsection 2.2.1, any implementation should be validated to ensure leakage and other artifacts are sufficiently suppressed. This section performs such a validation of the spectral analysis presented in the previous section. To this end, a dedicated analysis routine, tailored to the present data analysis and research focus of this thesis, was developed. The routine is presented in Subsection 2.3.1 and used in Subsection 2.3.2 to assess how accurately absolute distortion amplitudes as well as amplitude changes are detected in time-domain signals. The accuracy with which phase angles of distortions are calculated is also assessed.

2.3.1 Implementation: Validation Routine

To assess potential errors in the spectrum, a validation routine based on artificial data was developed and applied in the course of this thesis. This routine is the result of a continuous development process, including repeated extension to incorporate more parameters that influence the estimation error $[S1]^2$. Explicitly, the validation estimates the maximum error of the distortion amplitude, the phase angle, and the distortion frequency. Please note that the accuracy of measured data is not considered here; instead, the subsequent spectral analysis is validated.

² Special thanks to Gaurav Sharma for helping with the implementation of the analysis routine and performing tests for various parameter combinations to identify the most interesting dependencies.

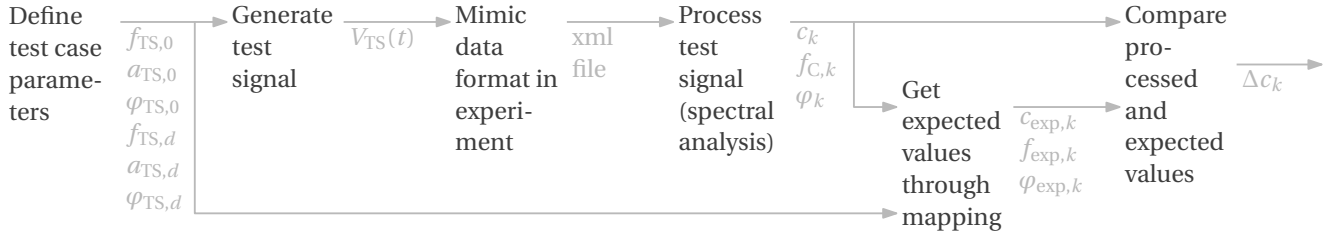


Figure 2.4: Schematic representation of the validation routine for the spectral analysis. Symbols defined in Equations 2.2, 2.3, 2.4, 2.5, and 2.6.

Figure 2.4 visualizes the validation routine. In short, it compares the known spectral content of a digital test signal with the processed spectrum extracted using the analysis routine in Subsection 2.2.2. Throughout the validation, the data handling remains identical to the measured data. In particular, the test signal is exported to the same file format that the measurement device uses before being processed by the analysis routine. In detail, the test procedure consists of six steps. All steps are implemented and run in MATLAB [54]:

1. Definition of the test case parameters: Fundamental frequency, amplitude, and phase angle, as well as frequencies, amplitudes, and phase angles of distortions, are selected.

fundamental frequency	$f_{TS,0}$,	
fundamental amplitude	$a_{TS,0}$,	
fundamental phase angle	$\varphi_{TS,0}$,	
total number of distortions	D ,	(2.2)
distortion frequencies	$f_{TS,d}$, $d = 1 \dots D$,	
distortion amplitudes	$a_{TS,d}$, $d = 1 \dots D$,	
distortion phase angles	$\varphi_{TS,d}$, $d = 1 \dots D$.	

2. Generation of the test signal based on parameters: First, a vector t of time stamps for the signal is generated. It has a duration of one minute and a sampling rate of $f_S = 25$ kHz (same sampling rate as measured data). Then, the single-phase test signal $V_{TS}(t)$ is generated by adding up all components (fundamental and distortions):

$$V_{TS}(t) = a_{TS,0} \cdot \cos(2\pi f_{TS,0} t + \varphi_{TS,0}) + \sum_{d=1}^D a_{TS,d} \cdot \cos(2\pi f_{TS,d} t + \varphi_{TS,d}). \quad (2.3)$$

3. Exporting the signal to the same format as the measured data. The data format of the resulting XML file is explained in Section 2.1.
4. Processing of the test data file using the routine described in Subsection 2.2.2: The analysis outputs the following values

spectral components	c_k ,	
at frequencies	$f_{C,k}$,	(2.4)
with phase angles	φ_k .	

5. Mapping of test signal components to the frequency bins $f_{C,k}$ of the processed spectra: As discussed in Subsection 2.2.2, the frequency bins $f_{C,k}$ depend on the analyzed time interval. The test signal frequencies $f_{TS,d}$ and the extracted frequency bins likely do not agree in value ($f_{TS,d} \neq f_{C,k}$). To know which values to expect in which bin, the test signal parameters have to be transformed to expected components with the same frequency base as the processed spectrum.

The mapping works as follows: The amplitude of the component is assigned to the nearest frequency bin of the processed spectrum. This gives the following values

$$\begin{aligned} &\text{expected amplitudes} && c_{\text{exp},k} \\ &\text{at frequencies} && f_{\text{exp},k} = f_{C,k}, \\ &\text{and expected phase angles} && \varphi_{\text{exp},k} \end{aligned} \quad (2.5)$$

6. Comparison of expected and extracted values: For each bin of the processed spectrum with frequency $f_{C,k}$, we have an expected $c_{\text{exp},k}$ and a processed c_k amplitude value. The relative amplitude error is defined as

$$\Delta c_k = 2 \cdot \frac{c_k - c_{\text{exp},k}}{c_k + c_{\text{exp},k}}. \quad (2.6)$$

2.3.2 Results: Changes in Distortion Amplitudes are Detected With High Accuracy

This subsection uses the new validation routine to assess how accurately the analysis extracts distortion spectra from the voltage or current time series. Knowledge of spectral accuracy is important for interpreting measured spectral data. Changes in voltage distortion are significant only if they lie well above the analysis's estimation accuracy. The first test case used for validation contains only harmonic distortions. Explicitly, the test case parameters are³:

$$\begin{aligned} f_{\text{TS},0} &= 50 \text{ Hz}, \\ a_{\text{TS},0} &= 230 \text{ V}, \\ \varphi_{\text{TS},0} &= 0 \text{ rad}, \\ f_{\text{TS},d} &= d \cdot f_{\text{TS},0}, \quad d = 2, 3, \dots, 80, \\ a_{\text{TS},d} &= 0.02 \cdot a_{\text{TS},0}, \\ \varphi_{\text{TS},d} &= \text{random number between } 0 \text{ and } 2\pi. \end{aligned} \quad (2.7)$$

The second test case has distortions at interharmonic frequencies. Explicitly, the following distortion parameters are set⁴:

$$\begin{aligned} f_{\text{TS},d} &= (-13 + d \cdot 15.3) \text{ Hz}, \quad d = 1, 2, \dots, 262 \\ a_{\text{TS},d} &= 0.001 \cdot a_{\text{TS},0} \\ \varphi_{\text{TS},d} &= \text{random number between } 0 \text{ and } 2\pi \end{aligned} \quad (2.8)$$

The fundamental frequency parameters ($f_{\text{TX},0}, a_{\text{TX},0}, \varphi_{\text{TX},0}$) for this interharmonic test case are identical to the harmonic test case defined in Equation 2.7. Both test cases are processed through the validation routine depicted in Figure 2.4.

Figure 2.5 visualizes the results of the test routine for a Fourier window/time resolution of 1 s. The initial test case parameters, as well as the expected and processed values, are compared in one plot. For each test case, an exemplary zoom into the frequency axis is shown to allow better differentiation between the data points. With a fundamental frequency of exactly 50 Hz, the frequency resolution of the processed spectrum is 1 Hz. Thus, the harmonic frequencies (integers) in Figure 2.5a always match the frequency bins exactly. The interharmonic test case in Figure 2.5b contains non-integer frequencies, for example, at 109.4 Hz. These lie between processed frequency bins. The expected amplitude is thus assigned to the closest neighboring bin. As a result, the maximum frequency error is half the bin width. The bin width depends on the width of the Fourier window. For the different time resolutions these are 0.5 Hz for 1 s resolution, 2.5 Hz for 200 ms resolution, and 5 Hz

³ Matlab function rand() was used for random number generation with a seed of 2 and the Mersenne Twister algorithm [58]

⁴ Matlab function rand() was used for random number generation with a seed of 3 and the Mersenne Twister algorithm [58, 59]

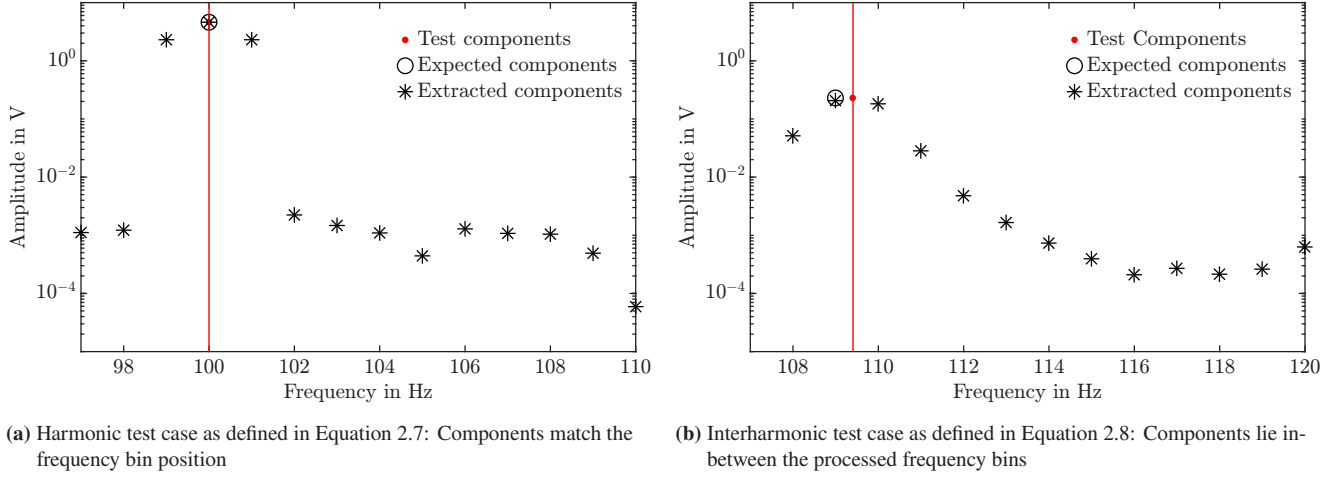


Figure 2.5: Validation routine applied to a harmonic and interharmonic test case shows the mapping between test signal parameters and processed spectrum.

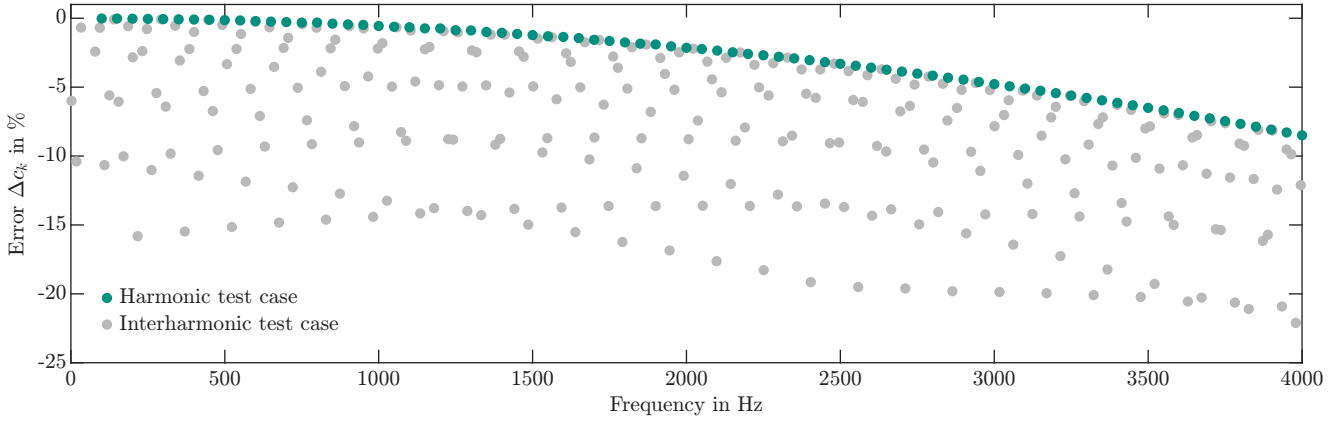


Figure 2.6: Amplitude estimation error for a Fourier window of 1 s is large at high frequencies, especially in the interharmonic test case.

for 100 ms resolution. All observed characteristics are the same in other frequency regions of the spectrum (not shown in the figure). However, the difference between the frequency of a test case component and the nearest bin in the processed spectrum changes with frequency.

Figure 2.6 shows the relative amplitude errors Δc_k for both test cases. Green points depict the results from the harmonics test case, while gray points refer to the interharmonic test case. The frequencies around fundamental ($50 \text{ Hz} \pm 15 \text{ Hz}$) are excluded from the analysis for two reasons: First, the amplitude of the fundamental is significantly larger compared to the distortion frequencies and significantly leaks into neighboring frequency regions. Resulting relative errors are not comparable to the low-amplitude distortions. Second, this thesis focuses on distortions and does not investigate the amplitude and frequency of the fundamental component. Only components actually imprinted onto the test signal are evaluated in the error estimation. The amplitude error is negative throughout. In other words, the analysis routine underestimates the amplitudes of distortions. Looking at the harmonics test case, the errors gradually increase with frequency but stay below 10% up to 4000 Hz. The errors in the interharmonics test case are much larger compared to the harmonics test case. In addition, they vary over a large range of errors and change from one test component to the next. This behavior is caused by the bin-matching explained in Figure 2.5. The distance Δf between a test case distortion frequency $f_{\text{TS},d}$ and its closest spectral bin $f_{\text{C},k}$ varies for each distortion component. This variation causes different errors in the interharmonics test case. The larger the difference Δf , the larger the underestimate of the spectral amplitude. In addition, similar to the harmonics test case, the error increases with frequency (see also [S1]). The amplitude estimation at higher frequencies is less accurate compared to lower frequencies.

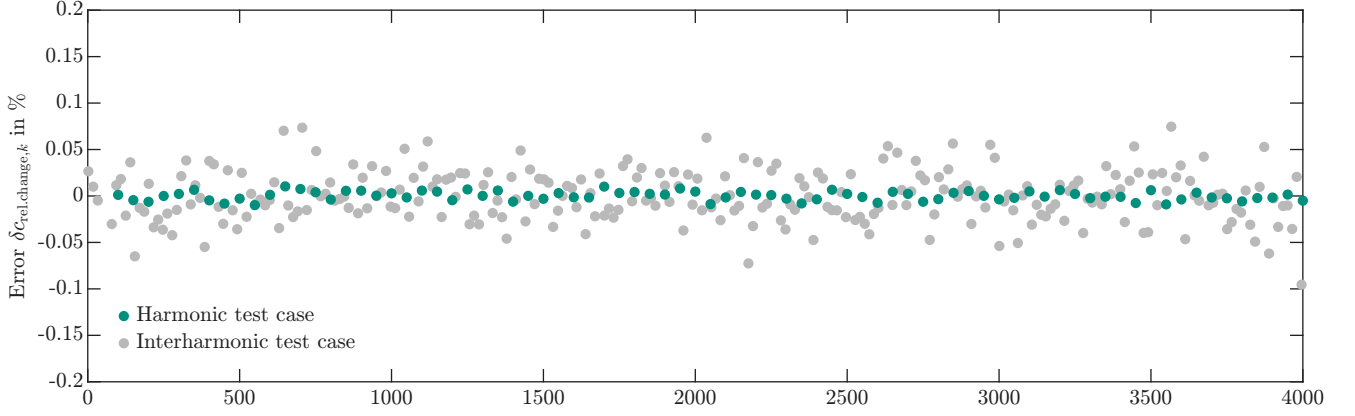


Figure 2.7: Error in detecting changes in distortions amplitudes is below 0.1 %. Error defined in Equation 2.11.

Section A.1 investigates the maximum amplitude errors for the other two time resolutions (200 ms resolution in Figure A.1a and 100 ms resolution in A.1b). The amplitude errors are much larger compared to the 1 s resolution presented here due to the reduced frequency accuracy and thus larger picked-fence effect.

Instead of absolute distortion amplitudes, this thesis mainly focuses on changes in distortions. To evaluate how accurately amplitude changes are detected, two additional test cases are introduced: A harmonic test case with double the distortion amplitude in Equation 2.7 and an interharmonic test case with double the distortion amplitude in Equation 2.8:

$$\begin{aligned} \text{harmonic amplitudes} \quad a_{\text{TS},d} &= 0.04 \cdot a_{\text{TS},0} \\ \text{interharmonic amplitudes} \quad a_{\text{TS},d} &= 0.002 \cdot a_{\text{TS},0} \end{aligned} \quad (2.9)$$

All other test case parameters remain the same (see Equation 2.7 and Equation 2.8). Both additional test cases are processed through the validation routine. The relative change in amplitude from test case A to test case B is represented by

$$c_{\text{rel.change},k} = 2 \cdot \frac{c_{\text{B},k} - c_{\text{A},k}}{c_{\text{B},k} + c_{\text{A},k}} \quad (2.10)$$

and is calculated for both expected $c_{\text{rel.change,exp},k}$ and processed $c_{\text{rel.change},k}$ amplitudes. Because the amplitudes are constant over all frequencies in both test cases (compare Equation 2.7, Equation 2.8, and Equation 2.9), the expected amplitude change is constant over all frequencies: $c_{\text{rel.change,exp},k} = 2 \cdot \frac{0.04 \cdot a_{\text{TS},0} - 0.02 \cdot a_{\text{TS},0}}{0.04 \cdot a_{\text{TS},0} + 0.02 \cdot a_{\text{TS},0}} = \frac{2}{3} \approx 66.7\%$ for the harmonic test case and $c_{\text{rel.change,exp},k} = 2 \cdot \frac{0.002 \cdot a_{\text{TS},0} - 0.001 \cdot a_{\text{TS},0}}{0.002 \cdot a_{\text{TS},0} + 0.001 \cdot a_{\text{TS},0}} = \frac{2}{3} \approx 66.7\%$ in case of the interharmonic test case. The error in amplitude change detection is the difference between the two:

$$\delta c_{\text{rel.change},k} = c_{\text{rel.change},k} - c_{\text{rel.change,exp},k} \quad (2.11)$$

Figure 2.7 presents the error in amplitude change detection. The processed amplitude change lies closely around the expected values, resulting in a small error value. The error in amplitude change detection is below 0.1 % at all frequencies. Both positive and negative errors occur, hinting at both over- and underestimates of the processed amplitude change. The error behavior does not change with frequency. Especially, the errors do not increase with frequency even though the absolute amplitude estimates are less accurate at higher frequencies (compare Figure 2.6). These low amplitude-change-detection errors are explained by the deterministic character of the potentially high-amplitude errors (leakage, picked-fence effect, compare Subsection 2.2.1). As long as the underlying binning and spectral content at certain frequencies remain similar, the absolute amplitude errors are the same. Small changes in amplitude are then detected with high accuracy. As the fundamental frequency in the power grid usually stays in a narrow range around 50 Hz, the binning of the spectral analysis remains the same at different points in time. The distortion spectrum is also quite characteristic and usually does not change much. For example, harmonic distortions always have higher amplitudes, especially at lower orders, while interharmonic content is smaller. Figure 2.7 is based on

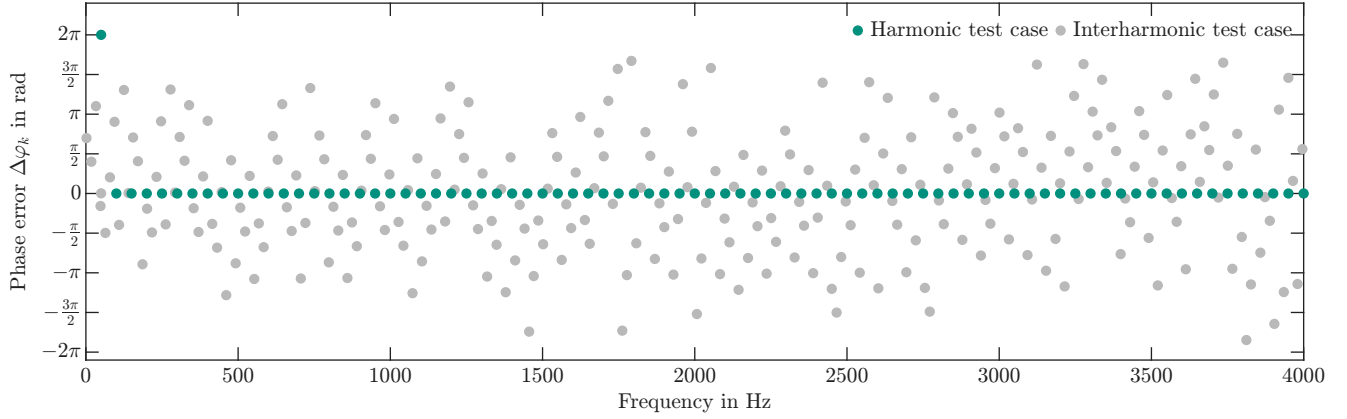


Figure 2.8: Distortion phase angle estimation error for 1 s Fourier window takes all values from 0 to 2π in case of bin-mismatch (interharmonic test case) and increases linearly with frequency for harmonic test case.

spectral analysis on 1 s Fourier windows. Section A.1 presents the same analysis for higher time resolutions (Fourier windows of 200 ms and 100 ms). In these cases, the accuracy of amplitude change detection is reduced, but the errors remain below 0.5 %.

Subsection 3.4.3 requires phase angle φ_k information on the distortions in addition to the amplitude. To assess the accuracy of the distortion phase-angles, the extracted phase angle φ_k and the expected value $\varphi_{\text{exp},k}$ as defined in the validation routine in Subsection 2.3.1 are compared. The absolute difference between the two is

$$\Delta\varphi_k = \varphi_k - \varphi_{\text{exp},k}. \quad (2.12)$$

Figure 2.8 shows the phase angle error $\Delta\varphi_k$ (Equation 2.12) for the spectral analysis in 1 s resolution of both the harmonic and interharmonic test case. For the harmonic test case defined in Equation 2.7, the phase angle estimation error (in green in Figure 2.8) is close to zero at all frequencies.

In contrast, the phase angle errors for the interharmonic test case defined in Equation 2.8 cover the full range from -2π to 2π and change largely from one test case component to the next. These large errors are caused by the same picked-fence effect introduced above. A bin in an FFT spectrum corresponds to an individual frequency $f_{C,k}$ and returns the phase angle φ_k of the signal component at exactly this frequency. This value will differ from the phase angle $\varphi_{\text{TS},d}$ of the original test signal component at frequency $f_{\text{TS},d} \neq f_{C,k}$. The phase angle error resulting from this picked-fence effect linearly increases with the frequency difference $\Delta f = f_{C,k} - f_{\text{TS},d}$. The picked-fence effect is especially pronounced for phase angles.

Figure 2.8 only presents the errors for a spectral analysis based on 1 s Fourier window. Section A.2 extends the investigation to the higher time resolution of 200 ms, and 100 ms. The other time resolutions show the same phase angle error characteristic: Errors at all values for the interharmonic test case and almost zero error for harmonic frequencies.

Overall, the validation reveals that the amplitude accuracy is highest for 1 s resolution and decreases for higher time resolutions (thinner Fourier windows). The amplitude accuracy also decreases with frequency. Components at low frequencies are detected more accurately compared to higher frequencies. The errors are mainly caused by the mismatch between the actual frequency of a distortion component in the signal and the frequency bins of the processed spectrum. With amplitude errors of up to -23% , the absolute amplitude accuracy is low, especially at high frequencies. The extracted phase angle values are also not reliable if the distortion frequency lies between spectral bins. Any phase angle investigations should focus on harmonic components. In contrast, changes in the amplitude of components are detected with high accuracy. Relative amplitude changes are detected with a precision of more than 0.5 % in all time resolutions and at all frequencies.

2.3.3 Summary and Discussion

A fundamental challenge in validating spectral analysis methods based on real-world measurement data lies in the absence of a known ground truth. Since the exact composition of measured signals is inherently unknown, alternative approaches are required to assess the accuracy and reliability of the analysis. To address this issue, a dedicated validation routine was developed for the spectral analysis described in Section 2.2. It is based on artificial, digital test signals generated in MATLAB, each comprising different combinations of harmonic and interharmonic distortion components. These signals are processed using the same analysis chain as the real measurement data, and the extracted spectral components are then compared to the known reference values. The results demonstrate that changes in distortion amplitudes are detected with high accuracy across all investigated frequencies and time resolutions. In particular, the error in detecting amplitude variations remains below 0.1 % for a Fourier window of 1 s. In contrast, the estimation of absolute amplitudes is less accurate, especially at higher frequencies. Similarly, phase angle extraction exhibits significant errors. The picked-fence effect is identified as the dominant source of error in the spectral estimation method. When a signal component lies between two frequency bins, its energy is distributed across neighboring bins, resulting in reduced peak amplitudes and increased uncertainty.

The validation setup offers several important strengths: It is specifically tailored to both the analysis method and the research objectives of this thesis. For example, the chosen range of test cases ensures that the validation encompasses the diversity and complexity of spectral content encountered in real-world signals. The inclusion of both harmonic and interharmonic components, as well as complex multi-component signals, further enhances the representativeness of the validation. Replicating the full data handling process, including data formatting and preprocessing, ensures that all relevant sources of error introduced along the analysis chain are properly represented. Most importantly, the consistently low error in detecting amplitude changes provides strong evidence of the method's robustness for the intended application. Nevertheless, certain limitations and challenges remain: In practical applications, the exact frequency of a component is not known a priori, and therefore, the observed spread across bins represents the highest achievable accuracy without employing additional techniques such as interpolation or zero-padding. Furthermore, the validation focuses exclusively on the analysis procedure itself and does not account for inaccuracies introduced during data acquisition. While relative changes in distortion amplitudes can be assessed with high confidence, absolute amplitude values should be treated with caution. They are suitable for qualitative comparisons, such as identifying dominant frequency regions, but may deviate from their true values due to spectral bin mismatch. Similarly, phase angle analysis should preferably be restricted to harmonic frequencies, which typically align more closely with the spectral bins and therefore yield more reliable estimates.

The validation confirms that the proposed spectral analysis is well-suited to the primary objective of this thesis, namely, the accurate detection of changes in voltage distortion amplitudes across a broad frequency range. It also shows that, despite careful methodological design, certain inaccuracies are unavoidable when analyzing discrete real-world signals in the frequency domain. Consequently, rigorous validation is an essential component of any spectral analysis approach, as done here. The results emphasize the importance of frequency resolution as a key determinant of accuracy. A finer resolution reduces bin mismatch effects and improves overall reliability. For this reason, the present work prioritizes the use of 1 s Fourier windows, corresponding to a frequency resolution of 1 Hz, over shorter windows with reduced spectral resolution.

Future work could extend the validation framework to explore additional signal characteristics and their influence on analysis accuracy. For instance, signals with fundamental frequencies deviating from 50 Hz could be investigated, which would cause the adaptive Fourier window lengths and thus lead to varying frequency resolutions. Such studies would further deepen the understanding of the method's performance under diverse conditions.

2.4 New Method: Innovative Field Measurement Scenario with High Spectral Resolution

This thesis aims to assess the influence of PV systems on voltage waveform distortions. The PV system could be a generator, amplifier, or uninvolved bystander of a specific distortion frequency. Available research on PV inverters in the context of voltage waveform distortions can be clustered into three groups: Simulative studies, laboratory tests, and field measurements. Each has its respective challenges and benefits.

Simulation studies investigate systems using a model representation of the physical hardware. They are especially useful for cases that cannot be realized in a laboratory or the real grid. For example, the investigation of severe distortion conditions could harm real hardware. A huge variety of PV system models exists; these are discussed in more detail in Subsection 4.1.1. They differ in simulation depth (e.g., switching vs. average) and complexity (e.g., isolated system vs. grid with several connected systems). Due to limited computational resources and the complexity of the real world, models are not capable of reproducing all characteristic behaviors of the system simultaneously. They are always designed for one specific research question. Which behaviors the model of a system can represent depends on the intended use of the model and, consequently, on the mechanisms considered during implementation. For example, a model designed to predict the power output of a PV system based on weather data without any internal modulation or switching processes implemented is too simple to predict the current waveform output of the inverter. In this respect, too simple models often do not accurately represent the investigated system [60, 61, 62, 63, 64]. Instead, dedicated models are needed; they require sufficient complexity and validation to correctly capture an effect.

Laboratory investigations are the second option for PV system investigation. They investigate individual inverters or entire PV systems using specialized hardware. For example, they are used to characterize the distortion behavior of PV inverters using impedance spectroscopy [65] or to analyze the effect a distorted grid voltage has on the inverter current quality [13, 14, 18, 66, 67, 68]. Because real hardware is investigated, which includes the actual system in all its complexity, all of the PV system's behavior is reflected in the data, whereas in simulation, only the effects considered in the model can be investigated. The laboratory environment is controlled and thus allows a wide range of manipulation on the system. For example, an inverter connected to a PV panel emulator can be operated at a set power as chosen by the researcher, while in the real-world grid, the weather determines the power setting. In the laboratory, all settings and conditions are reproducible, allowing the application of the same conditions to different devices under test. However, a dedicated laboratory with high-quality hardware is expensive, requires maintenance, and has a long setup time. In addition, the laboratory setup itself can impair the experimental result because its behavior differs from that of the real world. For example, a grid emulator might do very well at generating a voltage with chosen distortions, but still have a different impedance characteristic compared to the real grid with countless other loads and generators. The influence of the laboratory setup has to be studied in detail to correctly interpret the data.

The final option is to investigate PV systems directly in the field. This approach holds advantages on three levels:

- Field data is generally straightforward to access. The grid with PV systems is right outside the door and ready to be investigated. Without the need for a full laboratory setup, field data can be acquired with much lower monetary investment; only the measurement hardware is needed. This allows the capture of large amounts of data at various installations.
- In many cases, field measurements are the only viable option to investigate a system, as it cannot simply be disassembled and reassembled in a laboratory.
- The data acquired in-field captures the actual behavior of the system under investigation in its natural environment. In contrast, in simulation studies or laboratory investigations, the reduced complexity of the model or laboratory conditions that differ from the behavior of the real grid might influence the results.

Naturally, challenges also remain for field measurements:

- Any measurements taken or changes made to the system must be compatible with normal grid operation and not impair other players in the grid. In this context, extreme (and thus interesting) conditions only occur on rare occasions, if at all.
- There is a lack of control and reproducibility. The power output of the PV system is determined by the current weather conditions and cannot be actively changed. On the grid side, many different loads and generators are connected, each with its own individual and time-varying behavior that cannot be influenced. These determine the current grid condition, including the voltage distortion composition. No intentional variation of the voltage distortion composition is possible, and the condition of the grid cannot be recreated at a later point in time.
- It is impossible to have complete knowledge about the grid composition (what loads and generators are connected and how they behave) at any given time. This unknown manifold of loads and generators in the public distribution grid makes it difficult to discern the influence of an individual component (the PV system under investigation) from that of the rest of the complex system.

To exploit the advantages of field measurements while overcoming their challenges, this thesis proposes an innovative field-measurement method to assess the effects of PV systems on voltage-waveform distortion. The method must fulfill two requirements to overcome the identified difficulties. First, it must be applicable in the field with minimal, non-destructive impact on the system and the surrounding grid. Second, it has to exclude other potential influencing factors (other nonlinear loads and generators) to clearly attribute changes in voltage distortions to the system under investigation. The method's fundamental principle is to repeatedly disconnect and reconnect the PV system from the grid and simultaneously measure the grid voltage waveform in high resolution. Subsequently, voltage distortions with and without the system are compared.

2.4.1 Method 1: Induced Switching Directly Attributes Effects to the System Under Investigation

Voltage distortions present in the distribution grid are determined by the grid composition. The composition of the grid refers to the number, operation mode, and interconnection of loads and generators. Each component in the grid can be a generator, amplifier, or uninvolved in a certain distortion. The grid composition changes from one point in time to the next: different loads and generators are active at different times of day or draw/generate varying amounts of power. These alterations in grid composition can follow repetitive cycles or be completely arbitrary. For example, larger generators or consumers synchronize changes in their setpoint with the 15 min energy trading interval. Automated systems perform services at a fixed interval (for example, at the start of every minute). Some loads are preferably used at certain times, such as stoves for meal preparation around noon and in the evening. Others are used whenever the need arises, like elevators or cellphone chargers, without a set frequency. Renewable energy generation follows weather and daylight patterns. On a weekday, office buildings are under full usage, while on weekends, many of their computers, lights, and other equipment are shut down. Weather, season, and other environmental factors also influence what devices are operated and how much power they draw or generate. Overall, a multitude of periodic and non-periodic changes occur in the composition of the distribution grid.

Each of these changes can result in a change in voltage distortion. Equivalently, the system under investigation will alter the grid composition and thus voltage distortions. Changes in distortions due to grid components other than the PV system under investigation have to be separated from the influence of the system under investigation. To achieve this, it is forced to repeatedly disconnect from and reconnect to the grid following a carefully selected switching schedule. Analyzing switchings on different days and times of day allows looking beyond the volatility of the system and to identify common characteristics at all switching events. The larger the number of switchings implemented, the less likely it is that other generators and loads also alter their status at each switching event. Only one consistency over all switching events exists: The dis-/reconnection of the PV system. Observed characteristic changes in voltage distortions are then clearly attributed to the investigated PV system.

The method consists of five steps: installation of the measurement equipment, selection of the switching mode, definition of a switching schedule, running of the schedule and data acquisition, and subsequent analysis of the acquired data. In the following, each step is described in more detail. All steps and discussions are generalized to be applicable to an arbitrary

system under investigation. The discussion also addresses the special challenges that apply when investigating systems in the field. The measurement scenario and data analysis applied to a PV system in-field are also published in [O2]. In contrast to the 200 ms Fourier windows used in the paper, the analysis in this thesis uses 1 s Fourier windows to take advantage of the higher frequency resolution.

Installation of measurement equipment

The measurement method requires voltage measurements on the Alternating Current (AC) side of the system (between the inverter and the rest of the grid). Additional availability of current or power measurements (not necessarily in the same high resolution as voltage measurements) is beneficial, as they allow a more precise assessment of the system state (connected or disconnected). A variety of measurement devices (commercial, open-source, or in-house development) allow the acquisition of this kind of data. For example, the EDR introduced in Section 2.1 is optimized for long-term measurement of voltage and current time-series in high resolution. Inverters also already perform internal measurements. For example, regular power reports might be available. They can be accessed if an export and storage pipeline is implemented. Overall, the measurement equipment necessary for this method is easy to access and low-cost.

Concerning measurement device installation, commercial, private, or corporate power generation systems hold a first, obvious but not to be dismissed, challenge: doors and fences. Access to the system has to be granted via contacts to the owner or operator of the system, not only for device installation but also during data acquisition. The latter is necessary to monitor the experiment and to realize the switching of the system. A second difficulty is the availability of adequate measurement points. The voltage measurement requires a voltage tap, and current measurements using Rogowski coils require access to individual lines. Explicitly, in three-phase systems, each phase has to be accessible individually. For security reasons, such potential measurement points are specially secured, for example, inside locked switch/distribution boxes. As the system should remain unharmed, irreversible exposure of cables (cutting of isolation) is not a valid alternative, especially considering the security risk. At least one access point for measurement has to be identified. Measurements should ideally be taken as close as possible to the system under investigation. If more than one adequate measurement point is available, the one closest to the inverter should be selected. In most cases, the switching box in which the inverter is connected to the rest of the grid is the best candidate, provided it is accessible.

Each system of interest/under investigation has to be evaluated individually for its accessibility for measurements. After choosing the optimal measurement point, the measurement devices and data acquisition are installed. The installation of measurement equipment should only be performed by qualified/certified personnel and with the permission of the owner.

Selection of switching options

Different options exist for the realization of the switching, depending on the system. Each of the options has advantages and disadvantages depending on the system. They should be analyzed, discussed, and compared for each system individually before selecting an option. Hardware-based switching by hand is possible by disconnecting the circuit breakers between the PV system under investigation and the grid. Due to the manual nature of this option, at least one person with access to the switch box has to be present to implement the switching at all times. This will limit the total amount of time available for switching, and might be impossible during the weekend if access to the system is not possible then. Also, the exact switching times are difficult to realize, especially if several switches have to be operated. Another option is to disconnect the Direct Current (DC) side (solar panels) of the PV system. The inverter, without detecting available power on the DC side, will shut down or go to standby mode. Similar to the first option, this would require physical access to the inverter, and the inverter needs an accessible DC cutoff switch. If digital access to the inverter settings is possible, it can be commanded to shut down/disconnect. Such a software-based switching is easy to automate and thus allows for a large number of events and can follow the intended schedule exactly. However, access to the inverter control settings requires passwords that are usually only known to installers and manufacturers. All switching options may affect data acquisition; for example, internal inverter power reports may stop during system shutdown. Regardless of the selected switching mode, it must ensure that it does not adversely affect the system or nearby systems (e.g., by causing a sudden power drop). System operators, owners, other researchers investigating the system, and people responsible for surrounding grid structures have to be informed about the planned switching activities.

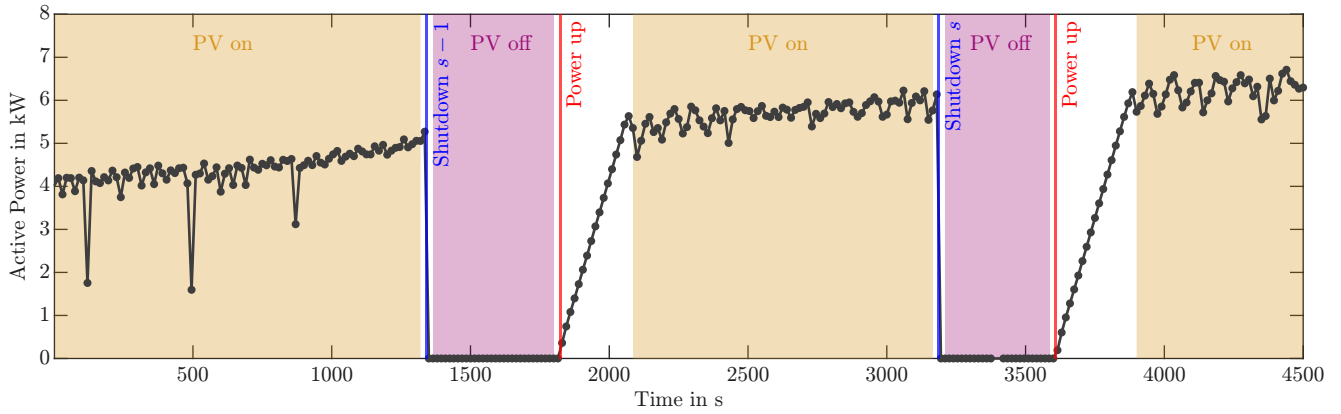


Figure 2.9: Power time-series of dis- and reconnection of PV system from the grid shows switching times and analyzed data ranges *PV on* and *PV off*.

Development of switching schedule

The switching schedule should include a high number of events distributed over a long range of times (preferably several days) and have a periodicity other than common grid composition changes. After the switching mode is selected, the switching schedule is defined. Ideally, switching should occur at different times of day and on different days. Preferably, both weekday and weekend days are included in the schedule. If days with sunny weather are selected, the switchings occur at a large variety of different operating powers and allow a power-dependent analysis. In between individual switching events (power-ups and shutdowns), the system should run in normal operation for a sufficient amount of time. Before reaching normal operation (running at full power), the system goes through several intermediate states, especially during power-up. These include MPPT ramp-up or grid observation and synchronization states. Waiting a long enough duration between switchings ensures that the system actually reaches normal operating states. In addition, a longer duration between switchings allows for aggregating distortion data over a long period of time and thus gives a better average estimate of present distortions. In contrast, longer time ranges between switchings limit the total number of events possible. Usually, seven to ten minutes between switching operations is enough to include transient processes and still provide sufficient duration of data during normal operation. If no additional data, like current or power estimates, is available, the switchings should be spaced further apart in time. In these cases, it is not possible to determine the state of the system (connected/disconnected) with high temporal accuracy, and large time gaps around the switching events are necessary. Finally, the repetition of switchings should avoid synchronization with the 15 min energy trading interval.

Data acquisition

Once the measurement device is installed, the switching mode is selected, and the switching schedule is defined, the actual acquisition phase is straightforward: The voltage waveform is continuously recorded while, in parallel, the switchings are performed following the schedule. If applicable, other grid components that have a large local influence on voltage distortions can be excluded during the experiment duration. For example, battery systems nearby can be deactivated during data acquisition.

Analysis and statistical evaluation of acquired data

After the experiment, two data sets are available: The acquired voltage time series in high resolution and the switching schedule. If possible, time series of other data, such as inverter currents or power feed-ins, are also available. The data analysis compares voltage waveform distortions with and without the system under investigation connected to the grid. It is implemented in Matlab [54] and follows these steps:

1. The exact switching times of the PV system are determined. The intended switching schedule gives a good hint at when, roughly, to expect switching events (dis- or reconnection). However, depending on the switching mode and possible transient processes, the exact times at which the system is fully operational or completely shut down can deviate from the intended schedule. If current or power data is available, the state of the system (connected or disconnected) can be

determined with high temporal accuracy (same resolution as current/power estimates). Figure 2.9 shows an exemplary snippet of power data that can be used to determine the exact state of the system. Shutdowns are visible as a drop in power output down to zero. After power-ups, the power increases back to its prior value. The power-ups are not instantaneous, but the MPPT takes several minutes before the maximum power point is reached. These intermediate states around the switching events are excluded from data analysis. The remaining time between each switching event is characterized by the system running in normal operation (no transients). These time ranges are referred to as state *PV on* or *PV off*. For example, the shutdown number s has a state *PV on* before the shutdown that starts at $t_{\text{on,start}}^s$ and ends at $t_{\text{on,end}}^s$. The state *PV off* after the shutdown s starts at $t_{\text{off,start}}^s$ and ends at $t_{\text{off,end}}^s$. These individual states *PV on* with duration $\Delta t_{\text{on}}^s = t_{\text{on,end}}^s - t_{\text{on,start}}^s$ and *PV off* with duration $\Delta t_{\text{off}}^s = t_{\text{off,end}}^s - t_{\text{off,start}}^s$ are highlighted in orange and purple in the power time-series in Figure 2.9. Extraction of start and end times from the power data can be automated using a threshold and time gaps before/after threshold interception. Current data (effective values) can be used analogously to power data. In case power or current data is not available, large time gaps around the switching times, as intended by the schedule, have to be excluded from analysis. These should be at least 10 min on either side of the event.

2. Voltage distortions are extracted from the data using the spectral analysis described in Subsection 2.2.2. The time-domain waveform data is segmented into consecutive 1 s Fourier windows before being transformed to the frequency domain. This results in a time series of voltage spectra $\mathcal{V}_k(t)$, one for each second.
3. The absolute voltage spectra for each state *PV on* and *PV off* separately are compared. Based on the extracted times, the voltage spectra $\mathcal{V}_{k,\text{on/off}}(t)$ are assigned to the states *PV on* or *PV off*. To get an assessment of the distortions, the median of all spectra extracted is calculated for each state individually. The resulting median spectrum quantifies the voltage waveform distortions present in the public grid during each state. Differences between the absolute distortion spectra for each state give a first hint at how the PV system influences the voltage waveform.
4. The relative difference between voltage distortions before and after a shutdown is calculated. The absolute distortion spectra of real-world low-voltage grid waveforms contain a large variety of distortion amplitudes present in the grid. Any changes in components with and without the PV system connected might be hard to discern among this multitude of components. Calculating the relative difference between distortion amplitudes before and after a switching event can highlight any changes present. It is beneficial to compare states that lie as close together in time as possible. The smaller the time lag between the two states, the higher the chance that the rest of the grid (other loads and generators) will remain the same, and any changes will result only from the system under investigation. Due to intermediate states of the inverter during power up (grid observation, synchronization, MPPT), the time difference between the state *PV off* and *PV on* is generally larger during power-ups compared to shutdowns. Thus, comparison of distortions before and after a shutdown is preferable instead of comparison around power-ups. Explicitly, the spectra are averaged (arithmetic mean) over each s -th state, resulting in average voltage spectra $\bar{\mathcal{V}}_{k,\text{on/off}}^s$. Then, the relative difference between distortions before and after a shutdown is calculated for each shutdown event s :

$$\Delta_{\text{rel}} \mathcal{V}_k^s = 2 \cdot \frac{\bar{\mathcal{V}}_{k,\text{on}}^s - \bar{\mathcal{V}}_{k,\text{off}}^s}{\bar{\mathcal{V}}_{k,\text{on}}^s + \bar{\mathcal{V}}_{k,\text{off}}^s}. \quad (2.13)$$

This results in a spectrum of relative differences that highlights any changes in distortions observed around the disconnection of the PV system under investigation.

5. Common characteristics over all switching events are evaluated. To get an overall representation of the change in distortions over all shutdowns, the median of all available differences (one for each shutdown) is calculated for each distortion frequency individually. The median is chosen instead of the arithmetic mean, as the data might not be normally distributed. In addition, if only very few shutdown events are available, the mean would be especially sensitive to outliers. The 5 and 95 percentiles of the differences are also considered. They allow an estimate of the variability in distortion change from one shutdown to the next. If each shutdown behaves quite differently, larger percentiles will

reflect that. In contrast, if every shutdown agrees on the magnitude of the distortion change, the percentiles will remain close to the median.

All analysis steps are performed separately for each phase a , b , and c . In summary, the analysis extracts five different sets of values from the acquired data: One voltage spectrum $\mathcal{V}_k(t)$ per second for the entire experiment duration, the start $t_{\text{on/off,start}}^s$ and end $t_{\text{on/off,end}}^s$ of states $PV\text{ on}$ and $PV\text{ off}$, average spectra $\bar{\mathcal{V}}_{k,\text{on/off}}^s$ for each state s , the relative differences $\Delta_{\text{rel}}\mathcal{V}_k^s$ between distortions before and after each shutdown s , and the median as well as percentiles over all shutdown events. These allow the characterization and quantification of the influence of the PV system under investigation on voltage waveform distortions in the connected grid in high spectral resolution while excluding other potential influencing loads and generators in the grid.

The method, so far, relies heavily on the induced switching operations (dis-/reconnection) of the system under investigation at selected points in time. However, many systems of interest might not allow such an interference with operation. For these cases (where switching cannot be induced/controlled), a less intrusive modification of the field measurement method is presented in the next section.

2.4.2 Method 2: Less Intrusive Measurement Approach

Section 2.4 presents a method to investigate the influence of a PV system on voltage distortions in field. It is based on forcing the system to shut down regularly and comparing the distortions with and without the system. However, forced switching might not be possible at every system of interest for a multitude of reasons. For example, the owner of the system might not like the loss of power resulting from the shutdown of the system. Or the control over the inverter state might not be possible due to restricted access. Repeated forced shutdown of a system at high power levels is not a designated usage of the system and carries risks that people might not want to take to characterize their system.

To investigate systems that do not allow induced switching, an alternative approach is suggested. All that is required is a long-term, non-intrusive voltage measurement at the connection point of the PV installation. The alternative method exploits the automated switching events of the PV system during everyday operation. In the course of a day, the PV system has two natural switching events: It powers up in the morning once enough sunlight is available and powers down in the evening once it gets too dark.

In principle, an identical analysis as presented in Subsection 2.4.1 for forced switching can be applied to the present, less-intrusive method. During normal operation, the state $PV\text{ off}$ lasts the whole night and $PV\text{ on}$ the whole day. Indeed, the voltage distortions close to a PV system were observed to be different during the night, compared to daylight hours [S1]. Twice a day, these two states of the grid with and without the PV system can be compared: Around the power-up in the morning and the shutdown in the evening. However, several parameters have to be carefully selected beforehand.

The state of the connected grid (its loads and generation composition) might change regularly and often over the course of a day and during the night. Averaging over a long duration of the states $PV\text{ on}$ and $PV\text{ off}$ incorporates this volatility of the system and gives good representations of the overall distortion composition. However, the continuous high-resolution voltage measurement on the system over a whole day equals a huge amount of data, but it contains only two switching events. In principle, a higher number of investigated switching events increases the significance of the results (compare Subsection 2.4.1). This is especially true for the non-intrusive method, as the switchings during normal operation occur at similar times each day, and the grid might change from one day to the next.

Instead of performing the spectral analysis on the entire voltage time-series, only a representative duration Δt_{ana} of voltage measurements before and after the switching is included in the comparison. This allows for incorporating many more days and thus switching events in the analysis for the same amount of computational resources. Δt_{ana} needs to be chosen long enough to ensure a representative amount of data is included instead of, for example, just a short snippet of exceptionally high or low distortion. Such a large range Δt_{ana} includes more volatility of distortions but requires high computational cost and

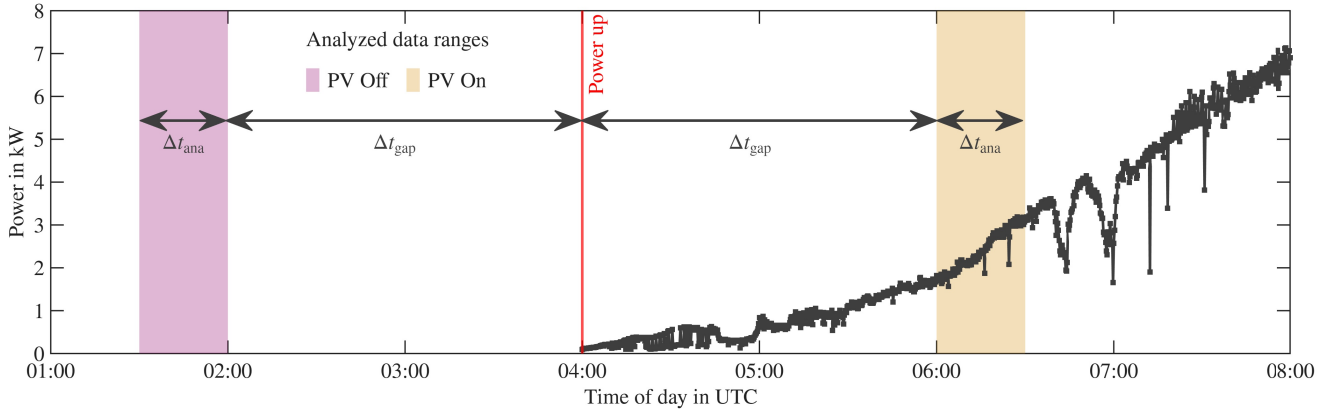


Figure 2.10: Analysis parameters for the non-intrusive field measurement method have to be selected carefully to balance the amount of data and quality of results.

thus reduces the number of days that can be included. So, at the same time, Δt_{ana} needs to be chosen short enough to allow the analysis of a high number of days.

Two intervals of data Δt_{ana} before and after the power-up in the morning, and another two in the afternoon before and after shutdown of the PV system are analyzed. A time gap Δt_{gap} is placed on either side of the switching, separating the analyzed interval of data Δt_{ana} and the time of switching. This time gap ensures that the system is already in a normal operating state or completely shut down before analyzing the distortions. The inverter might go through several steps before being in normal operation mode. In addition, inverters perform especially badly at low power, so the behavior might be more representative at higher power production. A large gap Δt_{gap} ensures that the system is completely shut down/powered up and in normal operating mode, but risks distortions changing due to other factors and not the PV system under investigation.

For each system under investigation individually, a detailed look at the power and voltage data of several days allows for selecting the best values for Δt_{ana} and Δt_{gap} . The dynamics and system behavior might be different for each system. An exemplary selection of parameters is shown in Figure 2.10. The power-up was identified at 4 am, and a gap of $\Delta t_{\text{gap}} = 120$ min is selected due to the slow startup process of the inverter. An analysis interval of $\Delta t_{\text{ana}} = 30$ min of voltage data before and after the power-up is analyzed for its distortion composition. A detailed description of how the parameters are selected is presented in Subsection 3.2.2. Several conditions that influence the choice are discussed there and applied to the system under investigation directly. The selection process is the same for each system, but the final parameter selection will change, depending on, for example, how fast the system powers up.

2.4.3 Summary and Discussion

Assessing the influence of PV systems on voltage waveform distortions directly in the field is essential, as it reflects the conditions under which these systems actually operate. However, in-field investigations are inherently challenging. The large number of loads and generators connected to the distribution grid complicates the attribution of observed effects to a specific component. In addition, the commercial nature and widespread deployment of PV systems require measurement approaches that are cost-effective, easy to implement, and minimally intrusive, so as not to interfere with normal operation or energy production. To address these challenges, this thesis presents a novel field measurement method. The method is specifically designed to quantify the influence of a PV system on voltage waveform distortions in the field. Its core principle is the repeated comparison of distortion levels with and without the system in operation. Whenever possible, this is achieved through actively induced switching events. Alternatively, a non-intrusive approach is proposed, utilizing naturally occurring switching events such as the daily startup in the morning and shutdown in the evening.

The proposed method offers several important advantages: It is straightforward to implement, relies only on low-cost and widely accessible voltage measurements, and enables a direct attribution of observed effects to the system under investigation. Its generalized design ensures applicability to a wide range of systems, and its focus on a high spectral resolution is suitable for detailed frequency-domain analysis. A further strength lies in the detailed post-processing of switching events, which ensures that transient effects are excluded from the evaluation. In addition, both implementation variants provide further complementary benefits. The induced switching approach allows for controlled events at different times of day, enabling power-dependent analyses and facilitating the decoupling of the PV system's influence from other grid dynamics. The high number of repetitions and the deliberate scheduling of switching events reduce the influence of confounding factors and allow for short time intervals between compared states. In contrast, the non-intrusive method enables long-term data acquisition across different days and seasons without interfering with system operation. Its non-invasive nature makes it applicable to almost any installation. Despite these strengths, several weaknesses and limitations must be considered. Both approaches require access to voltage measurements and, ideally, additional system data such as power or current measurements. The induced switching method introduces operational constraints, as it temporarily reduces power generation and requires coordination with system operators. These factors typically limit the duration of such experiments, restricting the analysis to a relatively short observation period. Furthermore, artificially induced switching, particularly during periods of high power production, may not fully represent normal operating conditions. The non-intrusive method, while operationally simpler, does not allow flexible switching timing and is therefore less effective at decoupling the influence of the PV system from other time-dependent grid variations. It also generates large data volumes, making comprehensive analysis challenging and necessitating the selection of representative subsets of data. In both approaches, parameter selection such as switching schedules, selected days, and analysis intervals can influence the results and must therefore be carefully considered. While the method is flexible and broadly applicable, it requires adaptation to the specific characteristics and constraints of each system. Careful experimental design and parameter selection are crucial to ensure reliable and interpretable results.

Independent of the measurement approach, the statistical robustness can be further improved by extending measurement durations and the number of included switchings. Further investigation of startup and shutdown dynamics could provide deeper insights into transient behaviors but is outside the scope of this thesis. In addition, the development of an automated parameter selection strategy, particularly for the non-intrusive approach, would further enhance the robustness and scalability of the method.

In conclusion, the presented field measurement method provides a practical and versatile tool for analyzing the effects of PV systems on voltage waveform distortions in real-world environments. By enabling clear attribution of observed effects and maintaining a high spectral resolution, it offers a significant advancement over existing approaches. The method is available in two complementary variants, allowing adaptation to system-specific constraints, and facilitates the investigation of PV systems directly in their natural operating environment. The next chapter will apply the method presented here to several PV systems.

2.5 Contributions and Future Work

Different approaches exist to investigate PV systems in the context of waveform distortions: Laboratory measurements, simulation studies, and field measurements. This thesis focuses on data acquisition directly in the field because it shows the real-world behavior beyond simplified model representations or laboratory setups. However, prior field investigations on PV systems lack spectral depth and do not clearly attribute observed effects to the system under investigation.

For this reason, an innovative field measurement method was developed in the course of this thesis. The new method allows for quantifying the effect of PV systems on grid voltage waveform distortions directly in-field. It maintains a frequency resolution of 1 Hz and, as such, goes beyond traditional investigations that focus on aggregated distortion values such as THD in high spectral resolution. By repeatedly comparing grid voltage waveform distortions when the PV system is active with those when the system is disconnected, the observed dependencies are undoubtedly attributed to the PV system under investigation, and other loads and generators are excluded as the root cause. In the primary methodological approach, the system under investigation is actively disconnected several times over the course of one or more days. An alternative, non-intrusive approach

using the natural switching of the system (power up in the morning and shut down in the evening), recorded on several days distributed all over the year, is also provided. The new field measurement method is ready to be applied to any grid-connected PV system if access for voltage measurements is provided.

Supplementary to the field measurement method, a spectral extraction algorithm was developed that identifies voltage and current distortion amplitudes and phase angles from the waveform data. The analysis is based on a FFT algorithm. It takes the special requirements of measured voltage and current waveforms into account by applying a dedicated data preparation before transformation. A validation routine for the spectral analysis is also provided. It shows that changes in voltage distortion amplitudes are detected with high resolution and identifies the bin-mapping (Picked-Fence effect) as the main source of error in absolute distortion amplitudes and phase angles. In other words, the spectral analysis is well-suited for the research question of this thesis. It accurately detects changes in the voltage distortion amplitudes at various frequencies simultaneously.

Future extensions to the contributed field measurement method and analysis routine include the investigation of frequencies above 4 kHz, or the automated identification of analysis parameters for the non-intrusive approach. These are discussed in more detail in Subsection 2.2.3, Subsection 2.3.3 and Subsection 2.4.3. To combine the benefits of both measurement approaches, the system under investigation could also be characterized by applying forced shutdowns on different days and times throughout the year. This includes seasonal changes as well as the arbitrary selection of switching times.

The ready-to-use new method is applied to several PV systems in the field to assess their influence on grid voltage waveform distortions in the following chapter.

3 Empirical Field Studies on Different Photovoltaic Systems

The previous Chapter 2 presented a new measurement method to characterize PV systems directly in the field. In this context, a PV system (or installation) refers to the entire setup, including the solar panels, the inverter that converts the DC power to AC, as well as the grid connection point with its individual characteristics. Using the new measurement method on three different real-world systems, this chapter characterizes, in detail, how voltage waveform distortions change due to the presence of PV installations. Section 2.4 discussed all experimental and data analysis steps required for the field measurement from a generalized perspective. Here, the specialized adaptations of the method to each of the investigated systems individually are discussed in addition to the results.

First, Section 3.1 presents the investigated systems and highlights their diversity in terms of power production, inverter manufacturer, and connected grid. Afterwards, the rooftop PV system is characterized in detail in Section 3.2 using both the induced-switching and non-intrusive method alternatives. The other two systems are characterized in Section 3.3, each with the methodological approach best fitted to the respective system. Finally, Section 3.4 presents additional impedance measurements and deeper voltage and current distortion analysis to consider possible root causes of the observed changes in voltage distortions caused by the PV systems.

3.1 Fundamentals: Investigated Photovoltaic Systems

This chapter presents field data measured at several PV systems. A total of three different, real-world, grid-connected PV systems are evaluated. The present section gives an overview of each of the systems. However, due to the limited information available on commercial devices due to proprietary restrictions, the systems largely remain black boxes. The inverter manufacturer and model are displayed on the device itself or on the owner's documentation. Subsequently, the related datasheet provides some information, but the internal circuits as well as the control algorithms of the systems remain unknown. In addition, the accessibility of the system for measurement device installation or manipulation of the operating state is different for each system. The PV systems are connected to a complex grid configuration: all of the other connected loads and generators, their underlying interconnection, and their current operating state. These are different at each grid connection point, change over time, and, most of all, are impossible to know in their entirety. Thus, similarly to the commercial PV system under investigation, the connected grid condition is also a black box.

Nonetheless, all information available on the systems is presented. The selected systems differ in terms of inverter manufacturer, system size, the connected grid, and the accessibility for measurements. Explicitly, the following systems are investigated: A rooftop PV system described in Subsection 3.1.1, a system within a power grid laboratory called SYSLAB in Denmark (see Subsection 3.1.2, and a large-scale PV field described in Subsection 3.1.3.

3.1.1 Rooftop Photovoltaic System

The first system under investigation is installed on a flat-roofed building of the Institute for Automation and applied Informatics (IAI), located on the KIT Campus North, near Karlsruhe, Germany. The exact location is 49.1° N latitude, 8.4° E longitude at an elevation of approximately 120 m above sea level.



Figure 3.1: Virtual building model with investigated rooftop PV system shows the orientation of both the building axes and inclination of modules. Picture taken from the 3D campus model of the KIT/IAI [69]. Special thanks to Karl-Heinz Haeefe for extracting this schematic.

A virtual model of the building with PV installation is depicted in Figure 3.1. The building under investigation is in the front. It is surrounded by other buildings and vegetation. The PV panels on the rooftop are distributed north and south of the roof access hood (brown); they are aligned with the main axis of the building (azimuth angle = 15°) and are alternately inclined east and west by 10° . All panels highlighted in a darker blue are connected to the inverter under investigation. All panels are of model IBC MonoSol 310 OS5. Each has a maximum power of 310 W under Standard Test Conditions (STC) and Normal Operating Cell Temperature (NOCT), a nominal voltage of 33 V, and a nominal current of 9.4 A. Their efficiency is 19 % [70]. The 208 PV panels add up to a total power output of 64.48 kW peak. Due to the surrounding vegetation, part of the system is subjected to shading in the early morning and late evening hours.

Figure 3.2 shows pictures of the north and south sides of the roof with the mounted PV panels. Both the north side (Figure 3.2b) and the south side (Figure 3.2a) of the roof are covered with panels. The PV system is connected to the grid via four inverters of type SMA STP 15000TL (three-phase, transformer-less) [71]. They are installed outside on the north wall of the roof hatch cover, as shown in Figure 3.4. Each inverter has a rated power of 15 kW and a maximum efficiency of 98.4 %. A cable routing through the wall connects them to the switch box inside the roof access cover.

Figure 3.3 shows a schematic circuit diagram of the PV system and measurement device. The EDR is connected between inverter number three and the grid connection busbar. It measures three-phase voltage and three-phase current. Current measurements are realized via Rogowski coils around each individual line. For more information on the EDR see Section 2.1. The measurements are taken at the connection point of the third of four inverters because the cables of this inverter have the best connection option for measuring windings. While all inverters are connected in the same way, the inverter under investigation (number three) is shown in more detail. The others are represented by the dashed ovals for simplicity. Four individual PV module strings are connected to each inverter. Figure 3.1 already highlighted all 50 panels connected to inverter number three in a darker blue. In addition to the voltage and current measurement by the EDR, the inverters themselves

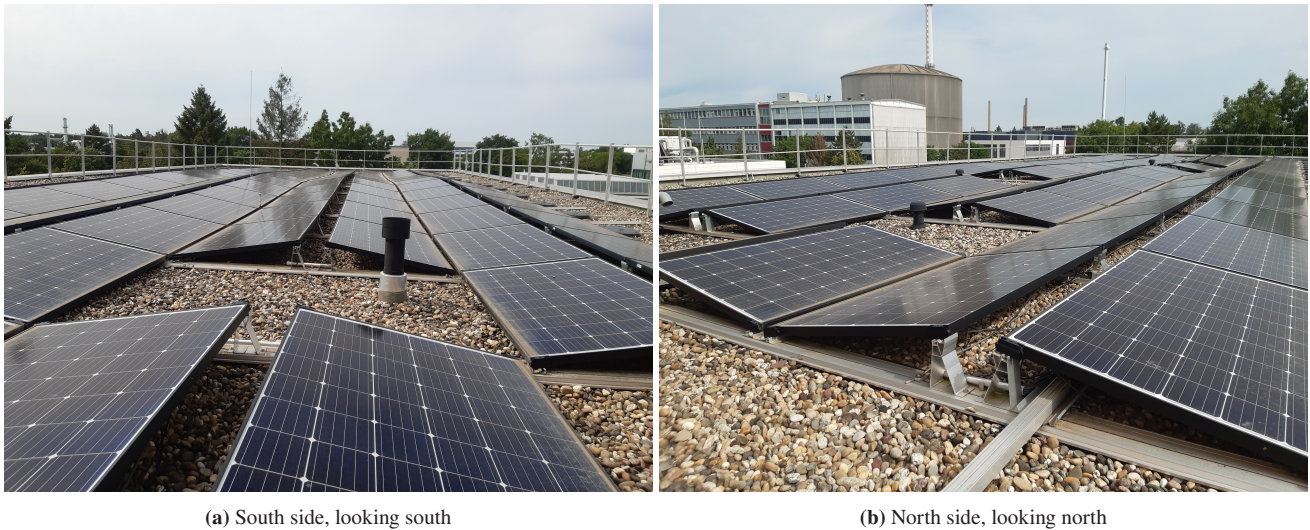


Figure 3.2: Pictures of the rooftop PV system on the north and south sides of the flat-roofed building.

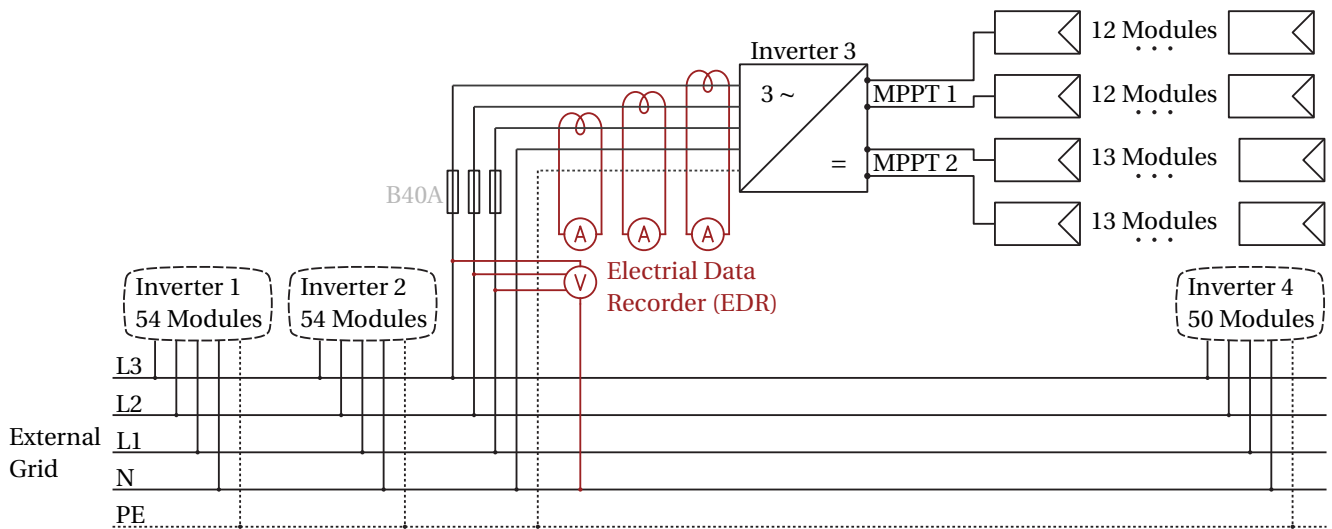


Figure 3.3: Circuit diagram of rooftop PV system and the connected measurement device. Diagram based on a figure by Denis Jakel; a similar version is published in [O2].

send power reports every 15 s. These reports are transferred to a database via the Modbus protocol and are available for later analysis.

Figure 3.5 shows a picture of the installed EDR device inside the roof-hatch cover. The inverter on the left-hand side of the picture belongs to an adjacent battery storage system. This system is disconnected during the measurement scenario described in the present section to avoid interference.

3.1.2 SYSLAB Photovoltaic System

The second system under investigation is located at the Energy System Integration Lab (SYSLAB) at the Department of Wind and Energy Systems of the Technical University of Denmark (DTU) [72, 73, 74]. The SYSLAB is an energy laboratory that, among other functionalities, allows the analysis and testing of renewable energy integration. It consists of several interconnected buildings, each providing different components, including PV power plants, wind turbines, storage systems, and heat pumps. Via different interconnections and circuit breakers, it allows a flexible setup of different configurations



Figure 3.4: Picture of the four inverters of the rooftop PV system located outside on the northern wall of the roof-exit hood.

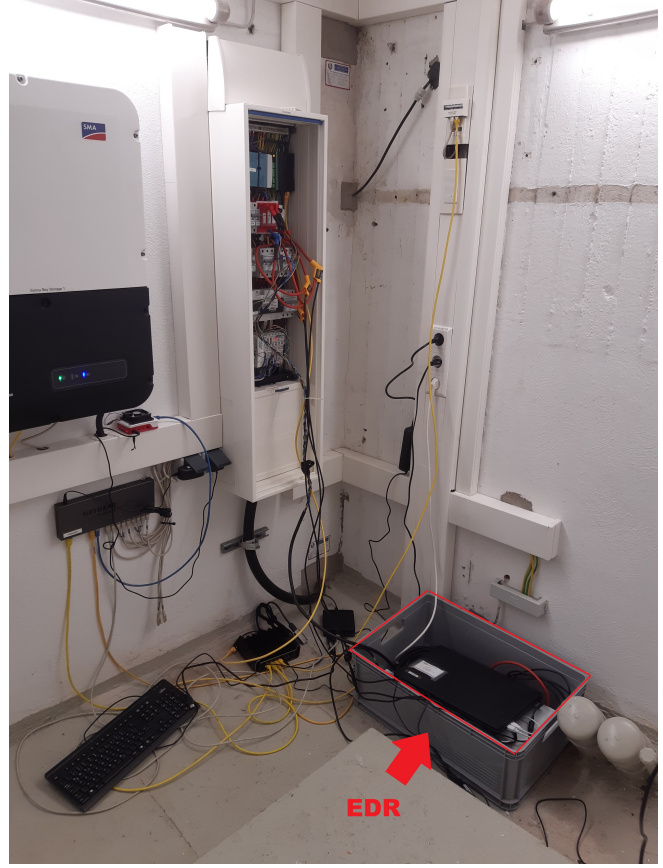


Figure 3.5: Picture of the EDR connected to the rooftop PV system. The measurement device is installed at the switch box inside the roof-hatch cover.

of the various components. The measurements at SYSLAB were performed in the course of the Whiplash Experiments in collaboration with the IAI. The experiments are part of the Transnational Access within the EU's ERIGrid 2.0 project [75]. They investigate the influence that cyber attack scenarios using Distributed Energy Resource (DER) can have on grid operation. The attacks use manipulation of inverter controls to create over- and undervoltage regimes [75].

The PV system that was investigated is connected to building 715 of the lab. Its generated power is fed into the grid via a transformer-less, three-phase inverter of model Symo 10.0-3-M by the company Fronius [76].

The circuit diagram in Figure 3.6 shows that the PV system can be operated in two different grid configurations: Either connected to the public grid or supplied by a grid emulator. All three lines of the three-phase system are represented by only a single line for simplicity. In the public grid, no other loads or generators within the SYSLAB infrastructure are part of the setup; only a direct connection to the public grid is activated. Of course, the public grid itself consists of a multitude of different loads and generators, and might well contain other PV sources. The second grid configuration is the same PV system connected to an isolated microgrid including a grid emulator. The grid emulator is an ABB Back-to-Back Converter. The interconnection of the PV system with the grid emulator includes several other loads, cables, and the PV system of the SYSLAB. The grid emulator is set to output an ideal sine voltage. Nonetheless, distortions can occur due to the non-ideality of the emulator or as a result of the other (nonlinear) loads participating in the grid-emulator configuration. For more information on the setup with the grid emulator, see [75]. Here, it is treated as a black box, the same as the public grid.

Figure 3.6 also shows the connection point of the EDR. The EDR as described in Section 2.1 is used to capture voltage and current measurements at the PV system. It is installed directly at the feed-in point of the system under investigation to the SYSLAB matrix in building 715. The Rhogovsky coils for current measurement are wrapped around the lines three times.

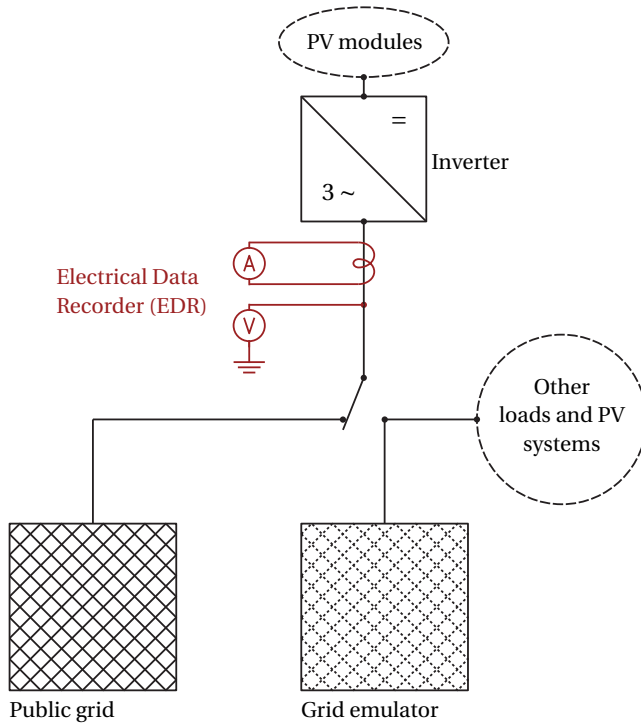


Figure 3.6: Circuit diagram of the investigated PV system in the SYSLAB with two different operating states: Connection to public distribution grid or isolated operation with a grid emulator.

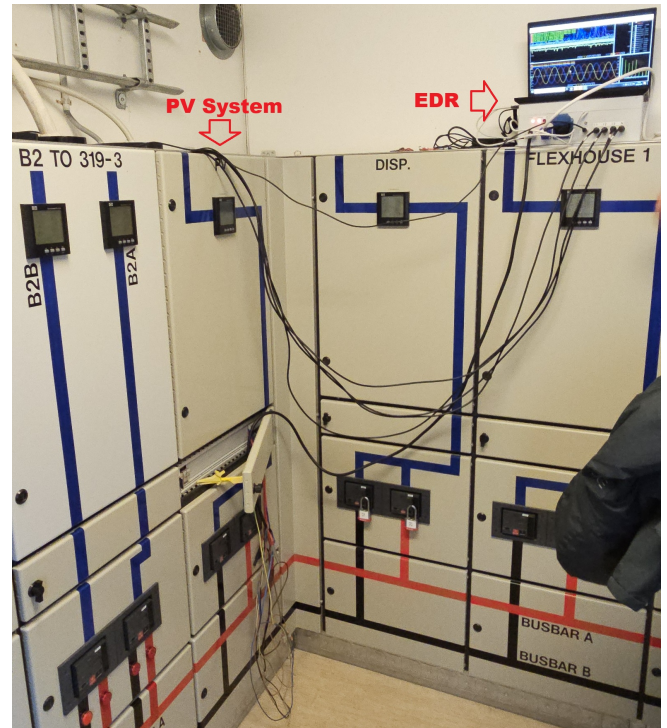


Figure 3.7: Picture of the EDR connected to the PV system in the SYSLAB. Special thanks to Kaibin Bao (KIT), Oliver Gehrke, and Kai Heussen (DTU,SYSLAB) for taking the picture during the measurements.

Any current measurements thus record three times the current actually flowing. Figure 3.7 shows the EDR device connected to the SYSLAB facility.

3.1.3 Photovoltaic Field

The third system investigated in this thesis was installed at the EnergyLab in 2013 [77, 78]. Figure 3.8 shows a schematic of the system. It consists of various blocks of PV modules, called tables, distributed over a field next to the main building of the EnergyLab. Overall, the PV field has a rated power of 1 MW.

One inverter per table converts the generated DC power to AC. The power from individual inverters is collected via eight power distribution boxes distributed across the PV field. It is then directly fed into the medium-voltage grid via the transformer at the center of the field. Different tables are equipped with different types of modules and inverters. The orientation of the modules also varies from one table to the next, both horizontally and vertically. This variety allows the investigation of different commercial PV systems under a multitude of conditions. In addition, the variation in orientation causes the power feed-in of the system to be distributed over the entire day instead of having one large power peak around noon.

This thesis analyzes voltage and current measurements taken at the inverter on table number 56. This inverter was chosen based on its minimal spatial distance to the power distribution box. Access for measurements is only possible in these power distribution boxes. In addition, the selected table is located in the northern part of the field. This region is unaffected by shading from the trees at the southern and eastern borders. Table 56 is equipped with 36 panels and is highlighted in red in Figure 3.8. The inverter is of type PIKO 10.1 DCS by the company KOSTAL Solar Electric [79, 80]. The corresponding power distribution box number two is located directly next to the table. This is where the EDR is installed (see picture of the

DiDiMoS - 3D Digital District for Energy Monitoring and Simulation

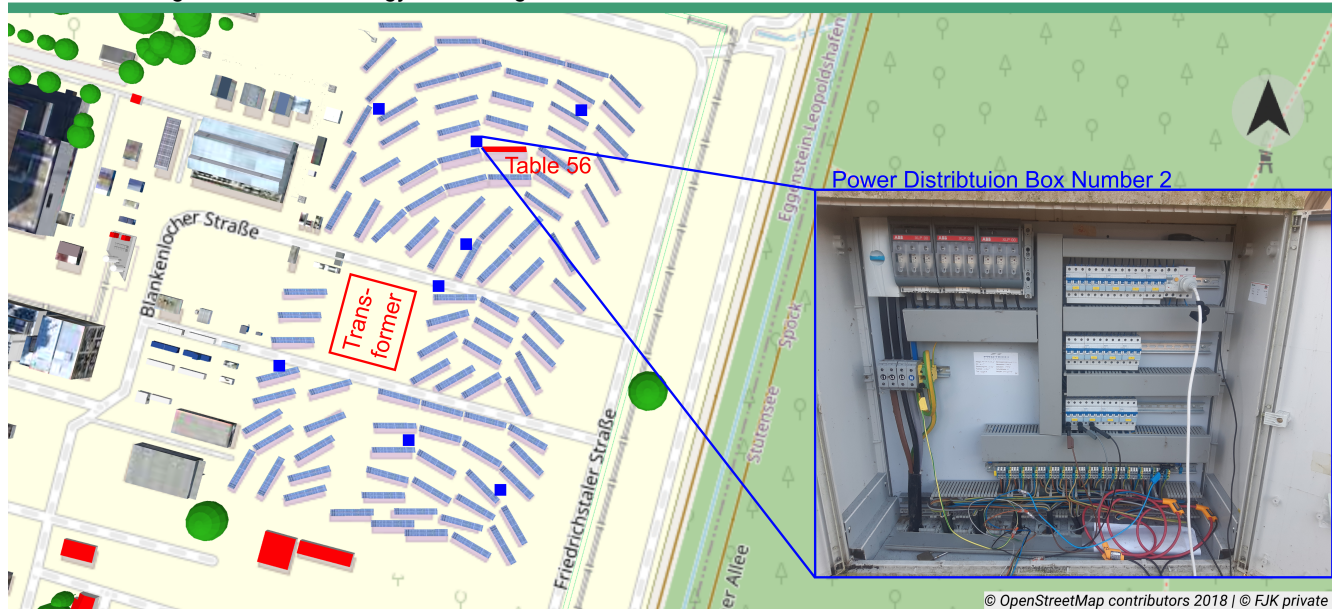


Figure 3.8: Schematic overview of the PV field at the EnergyLab. Measurements taken at the inverter of table 56. Schematic taken from the 3D campus model of the KIT/IAI [69].

inside of the box in Figure 3.8). The measurement at the PV field is made possible thanks to Alexander Höllhuber, Siegfried Heinrich-Sowa, and Michael Mast¹.

3.1.4 Summary and Discussion

A large number of PV systems are currently deployed in distribution grids, differing significantly in terms of installed power, geographic location, grid conditions, and inverter manufacturer. This inherent diversity poses a challenge for systematic analysis, as system-specific characteristics strongly influence their interaction with the grid. In this section, three distinct PV systems are introduced: a rooftop installation, a system installed in a laboratory environment in Denmark, and a large, 1 MW PV field. All three represent real-world, commercial systems. As with all proprietary grid-connected equipment, only limited information is available regarding their internal circuitry and control strategies.

A key strength of the selected set of systems lies in its diversity. The considered installations cover a wide range of power levels, grid conditions, and inverter technologies, thereby providing a representative subset of typical PV systems encountered in practice. This variability supports the generalizability of the findings and allows for comparative analysis across different configurations. At the same time, certain weaknesses and limitations must be acknowledged: All investigated systems are located in or near research facilities, and therefore may not fully reflect operating conditions in, for example, densely populated urban environments. Furthermore, access conditions differ between systems, leading to varying levels of measurement and installation possibilities. While research-oriented systems typically allow easier access, this may not be the case for privately owned installations. These observations highlight an important implication: each PV system exhibits individual characteristics, requirements, and constraints, resulting in a high overall variability.

The three systems presented here cover a broad range of these real-world conditions and thus provide a diverse and practically relevant basis for investigations. In the following sections, all the systems will be characterized in terms of their influence

¹ Alexander Höllhuber installed the necessary power outlet for the measurement device in the power distribution box and connected the device; Siegfried Heinrich-Sowa and Michael Mast provided necessary information on the PV field, e.g., a list of inverter models installed close to distribution boxes, and granted access to the facility for measurement device installation.

on voltage waveform distortions. The applied methodology can also be readily transferred to further systems. In the future, including even more PV systems will enhance the robustness and representativeness of the analysis. New opportunities include the new PV systems installed on neighboring institute buildings, as well as privately installed systems of institute members.

3.2 Results Rooftop Photovoltaic: Effect on Grid Voltage Distortions is Frequency-Sensitive

Section 2.4 introduced a new methodology to investigate in-field PV installations towards their influence on voltage waveform distortions. Here, the method is applied to the rooftop PV system introduced in Subsection 3.1.1. Explicitly, both the robust method relying on induced shutdowns of the system (see Subsection 2.4.1) and the non-intrusive approach based on the switchings occurring during normal operation (see Subsection 2.4.2) are applied to the same system. First, Subsection 3.2.1 presents measurements acquired with the induced switching approach. These measurements and results are also presented in a publication [O2] but using a different underlying frequency resolution and in [S1] but with less data included in the analysis. Afterwards, Subsection 3.2.2 uses the non-intrusive approach on the same system and compares the results of both approaches.

3.2.1 Method 1: Photovoltaic System Simultaneously Increases and Decreases Voltage Distortions

Section 2.4 presented a new field measurement method that is capable of quantifying the influence of PV systems on voltage waveform distortions in high spectral resolution. The method is based on repeatedly comparing voltage spectra with and without the system under investigation connected to the grid. Here, this method is used to characterize the rooftop PV system described in Subsection 3.1.1. Because the system is installed for research purposes on top of an institute building, it allows more extensive access, both physical and software-based, compared to other commercial PV systems in private or corporate hands. This allows the usage of the active characterization method as described in Subsection 2.4.1 that relies on forcing the system to shut down at different times of day. In contrast, if this active switching was not possible, the alternative, non-intrusive approach as described in Subsection 2.4.2 would have to be used. According to Subsection 2.4.1, the method requires careful preparation, including three steps: the installation of the measurement equipment, the selection of the switching mode, and the definition of the switching schedule. These are described in detail below for the special case of the rooftop PV system. Afterwards, the data acquisition and subsequent analysis are presented.

Installation of measurement equipment

The accessibility for measurement, as well as the measurement device installation, are described together with the system characteristics in Subsection 3.1.1. This experimental setup records voltage and current measurements from the EDR in 25 kHz resolution as well as the internal power reports from each of the four inverters of the system every 15 s.

Selection of switching options

Two different switching options exist for the rooftop PV system: It can be disconnected using both hardware and software operations. For hardware-based switching, the electrical fuses between the PV system and the distribution grid are disconnected by hand (see B40A in Figure 3.3). For this, the fuses for all four inverters and all three phases have to be switched individually. As a result, the switching of the whole system is not instantaneous. But afterwards, the system is reliably and physically disconnected and cannot have any influence on the remaining grid. Physical disconnection of the solar panels from the inverters is also possible, but is not considered further as a switching option for two reasons: It requires roof access to the inverters installed on an exterior wall, while the switch box is located inside. In addition, the physical disconnection of the system on the AC side is favorable because it includes all inverter components, independent of their potential reaction to a

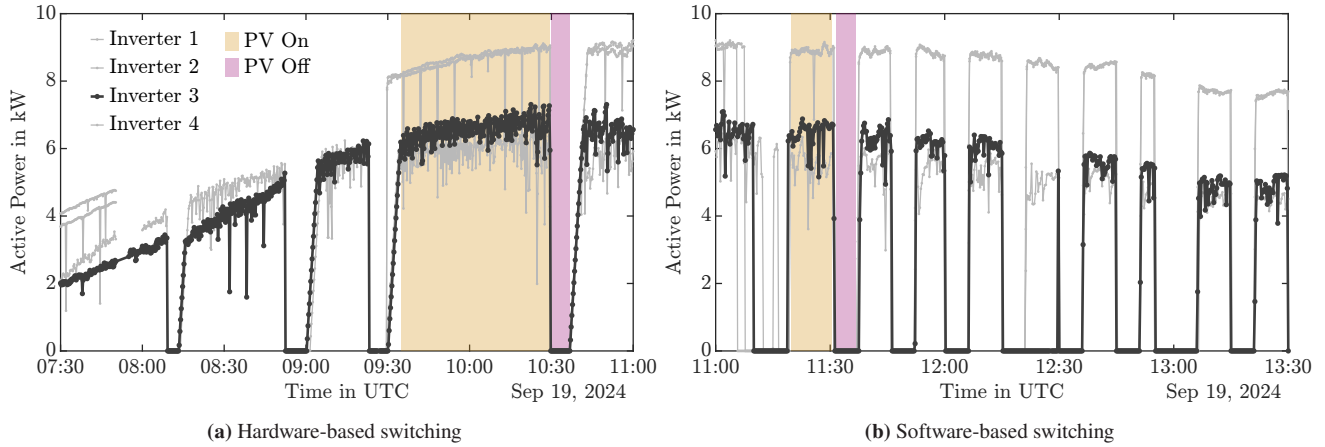


Figure 3.9: Power profile of rooftop PV system for software- and hardware-based switching shows slow ramp-up of power after physical disconnection.

disconnected DC input. The software-based switching approach is based on communication with the inverters.² The state of the individual inverters is controlled via Modbus on the local network. GNU's at daemon schedules all Modbus interactions. The communication scripts are based on previous work by [81, 82]. They implement the SunSpec specification, which was later standardized as IEEE 1547. Explicitly, holding register 40018 is used for fast shutdown. It was not necessary to use SMA Grid Guard Code [83].

In the course of preparatory measurements, the two switching options for the system are compared. Figure 3.9 shows the power records acquired during these tests. The power reports of all four inverters are compared. As the voltage measurements were conducted at inverter number three, this inverter's power reports are depicted in black, while the data of all other inverters are gray. Both the hardware-based switchings in Figure 3.9a and software-based shutdowns in Figure 3.9b are visible as repeated drops of the power output of all inverters down to zero. The shutdown of the system is reasonably fast in both cases, faster than the 15 s power reports of the inverters can resolve. In hardware switching, the power ramps up gradually after reconnection. This is due to the maximum power point tracking of the system, which is restarted after a complete shutdown. This means that a wait of several minutes is necessary before the system is back at its normal operation. In contrast, with software switching, the power output jumps up to the prior level right after reconnection. As the inverter remains active, the power feed-in can resume at the maximum power point saved internally.

In the case of hardware switching in Figure 3.9a, several sections of power data are missing. The power reports do not reliably resume after a hardware disconnection of the inverter. A more reliable resumption of data reports can be achieved by resetting the system before switching operations. A reset equals complete disconnection of the inverter on both the AC and DC side for several minutes to force a fundamental re-initialization. Figure 3.9b shows that, in software switching, not all inverters react at the same time, even though the commands are sent almost simultaneously. The inverters also do not always react to a single command. For example, just before 12:30, not all inverters turn on again. As a result, the commands were resent up to three times to make the switching more reliable.

During software-induced switching, a distinct clicking sound is audible in the inverters. This suggests that a physical disconnection of parts of the system occurs, and thus behaves quite similarly to the physical hardware switching. To test this assumption and compare the influence of the switching method on the experimental results, voltage waveform distortions are compared for both options. Explicitly, Figure 3.10 compares the changes in voltage waveform distortions from before to after switching off the PV system for both switching options. Figure 3.9 marks the time ranges of voltage data used for this comparative analysis. Two characteristics are visible: At frequencies below 500 Hz and around 3000 Hz, the two switching

² Special thanks to Kaibin Bao for providing the software, conducting preparatory tests, and running the switching schedules.

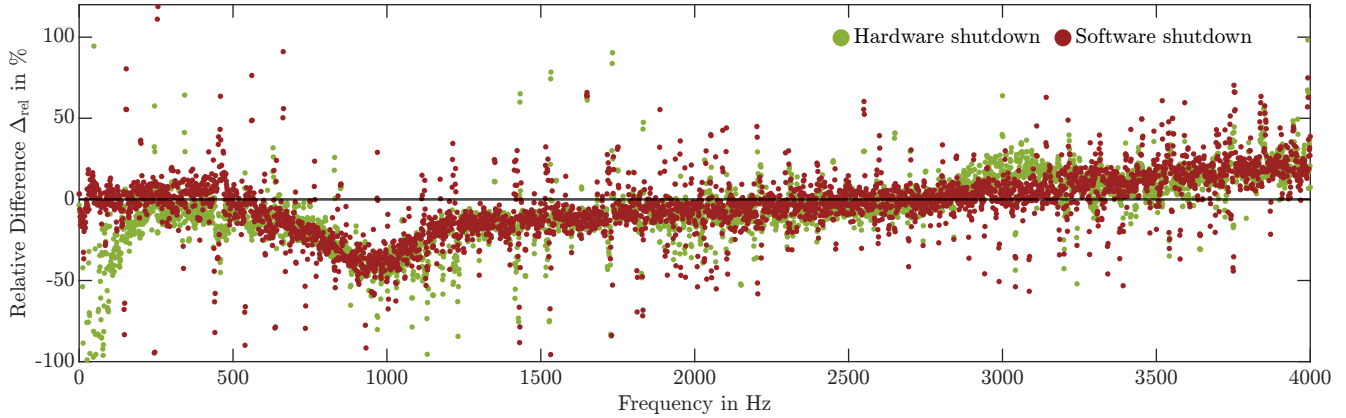


Figure 3.10: Change in voltage distortions compared for hardware and software switchings shows the same influence in a majority of frequencies.

options show different changes in distortions. At all other frequencies, especially concerning the significant drop in differences around 1000 Hz, the results for both switching types agree.

Software-based switching is chosen for the final implementation. A software-based startup is much faster compared to hardware switching (see also [S2]). In addition, the switching is easily automated and thus allows a high number of events on a reliable schedule without the need for physical supervision.

Development of switching schedule

The following switching schedule was chosen for investigating the rooftop PV system: It is repeatedly switched off for 5 minutes and then switched on again for 7 minutes (see also [S2]). This schedule allows a long enough duration of the states *PV on* and *PV off* and thus stable operating conditions. At the same time, it also avoids synchronization with the 15 min energy trading intervals. The schedule runs between 9:00 and 17:00 Central European Summer Time (CEST), covering the peak irradiation of the day, and is applied on two consecutive days: Friday, 20th September 2024 (weekday) and Saturday, 21st September 2024 (weekend). This includes variations in grid conditions due to consumer behavior (working day versus weekend) and usage of work-related gadgets. Both measurement days are characterized by clear weather, resulting in a large variety of PV power input.

Data acquisition

With these preparations and choices, the rooftop PV system is ready for characterization. Continuous measurements were conducted on the 20th and 21st of September 2024 while simultaneously running the described switching schedule. Afterwards, two sets of data are available: The power output $P_i(t)$ reported by each of the four inverters $i = 1, 2, 3, 4$ in 15 s resolution, and the voltage waveforms $V(t)$ for all three phases a, b , and c , sampled at 25 kHz.

Figure 3.11 shows the power output of the rooftop PV system during the two measurement days and thus the implemented switching schedule. Three characteristics are visible in the figure: First, the power for all inverters increases and decreases gradually over the day, representing a typical day profile for cloudless weather. Second, each inverter shows a distinct power profile. Inverters 1 and 2 show overall higher power and a stronger increase in the morning, while inverters 3 and 4 achieve less maximum power and overall more volatile values. The differences in power feed-in between the inverters are due to the different number of and positioning of connected panels, compare Subsection 3.1.1. Inverters 3 and 4 show reduced output and delayed morning startup due to shading on the north side. Finally, the shut-down periods of the PV system are visible in the distinct drop-downs of the power down to zero for all 4 inverters.

The switching starts after the system has been powered up for more than an hour in the morning. Interestingly, during the first few start-ups in the morning, the power of inverters 3 and 4 does not instantaneously jump up to the same level as before the shutdown, but gradually increases. This is not the case for inverters 1 and 2, as well as the power-ups later in the day. The special power behavior of inverters 3 and 4 was not clarified conclusively. A possible explanation includes the activity of the

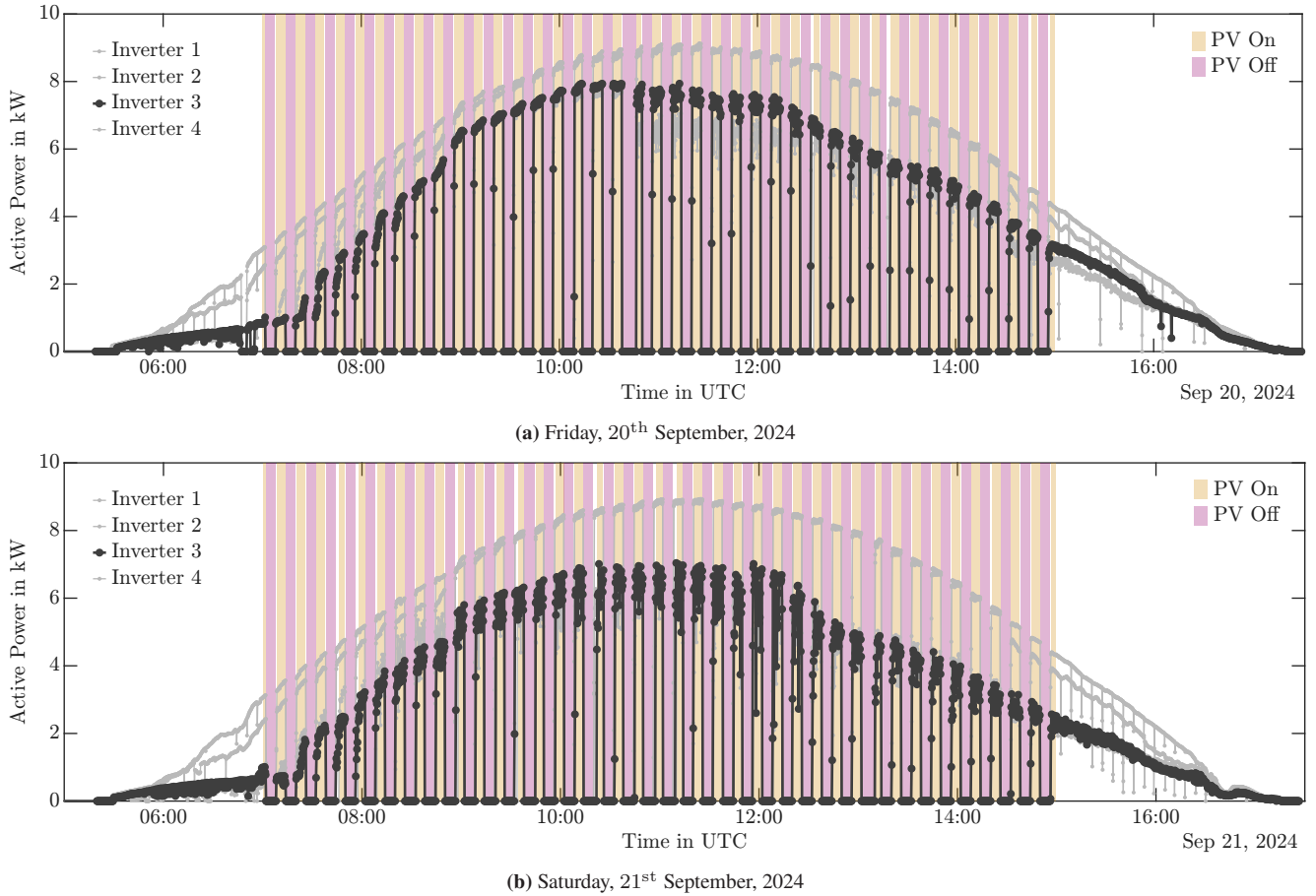


Figure 3.11: Power output of the rooftop PV system during induced switchings shows repeated power drops down to zero.

Tigo Cloud Connect Advanced system [84]³. The system is installed to improve performance on the DC side by bypassing individual modules that are shaded or otherwise compromised. It is possible that the system falsely bridges single modules due to reception issues or as a result of the shutdown. In any case, this behavior is suspected to be system-specific and is not discussed further.

A closer analysis of the data in Figure 3.11 reveals that the shutdown times match the intended schedule accurately. As the shutdown command is treated as an emergency response, its instant execution was expected. Contrarily, the restarting times of the inverter do not exactly correspond to the set schedule but rather show varying delays of up to several minutes. This is likely because the reactivation command is not treated as an emergency response and therefore has lower priority. The four different inverters do not always respond at the same time. These small time delays between the reaction of the inverters to the switching signals are taken into account in the subsequent data analysis.

Analysis and statistical evaluation of acquired data

According to Subsection 2.4.1, the analysis of acquired data includes five steps: the exact determination of switching times based on power data, the spectral analysis of all voltage data, the comparison of absolute distortions, the calculation of relative differences for each shutdown, and the evaluation of common characteristics over all shutdowns. These steps are described in more detail in the mentioned methods section. Here, only special adaptations to or parameters chosen for the current system under investigation (the rooftop PV system) are described.

³ The Cloud Connect Advanced system used is CCA 336-20000-10 together with TS4-R-O

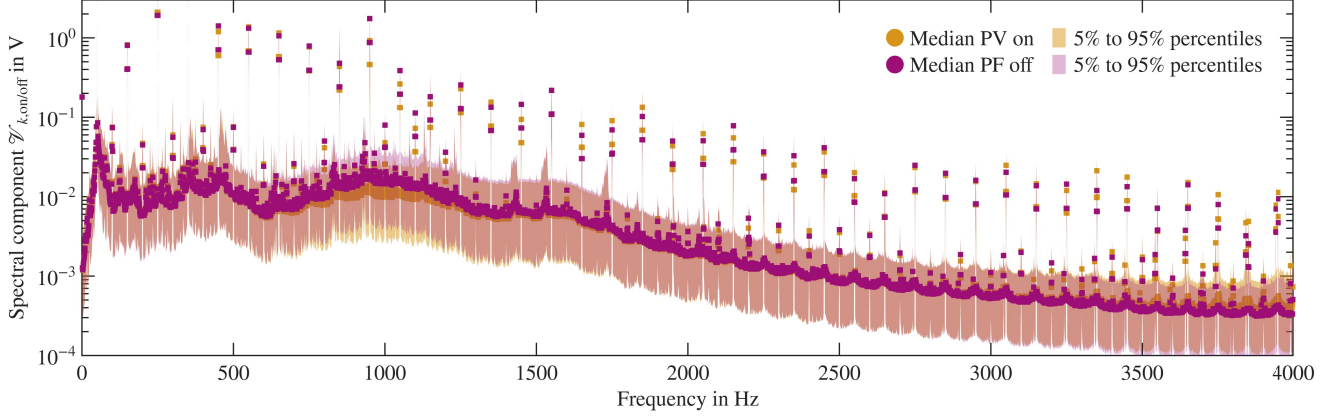


Figure 3.12: Voltage distortions at the rooftop PV system show a complex spectrum both with and without the system connected.

The exact timing of the power-up and shutdown times is derived based on a threshold of 100 W applied to the power data in Figure 3.11. The state *PV on* is the time interval between a power-up and the subsequent shutdown during which the system is fully operational. Explicitly, $t_{\text{on,start}}^s$ is defined as the time from which all four inverters report power above the threshold, plus a time gap of 10 s. This ensures that all inverters are connected and fully operational. $t_{\text{on,end}}^s$ is the point in time before at least one inverter reports a power below the threshold minus an extra gap of 2 s. The following state *PV off* after the disconnection of the PV system is defined similarly: $t_{\text{off,start}}^s$ is the time from which on all four inverters report power below the threshold plus a safety margin of 2 s. $t_{\text{off,end}}^s$ is the point in time before at least one inverter reports a power above the threshold minus a gap of 10 s. The safety margins of 10 s around power-ups are chosen larger compared to the 2 s around shutdowns because the power-up of the system is less instantaneous compared to the shutdown. Because not all inverters react to the switching command at the same time and because of the use of the safety margin, there is an intermediate time interval between the states *PV on* and *PV off* that is excluded from analysis ($t_{\text{on,end}}^s \neq t_{\text{off,start}}^s$). An alternative threshold value and safety margin for automated switching time determination is used in [S2]. A total of 80 shutdowns were recorded over the two measurement days. They occur at different times of day, at different inverter powers, and on a weekday as well as a weekend day.

Next, all voltage data from 7 am to 3 pm Universal Time Coordinated (UTC) on both measurement days are transformed into a time series $\mathcal{V}_k(t)$ of consecutive voltage spectra. The used spectral analysis is described in detail in Subsection 2.2.2. No special adaptations of the method to the system under investigation are necessary. Afterwards, based on the found start and end times, the individual spectra $\mathcal{V}_{k,\text{on/off}}(t)$ are assigned to the states *PV on* and *PV off*.

Figure 3.12 shows median and percentiles of all distortion spectra $\mathcal{V}_{k,\text{on/off}}(t)$ separated by their assigned state *PV on* or *PV off*. All spectra when the PV system is fully operational or shut down are included, independent of the time of day. Explicitly, no aggregation (averaging) of data was performed at this stage; instead, each individual voltage spectrum (one for each second of voltage data) was considered for the median. Orange data points show distortions when the PV system is connected. Without the system connected, the data points in purple are present. Both spectra are plotted together on a logarithmic y-scale. The fundamental component at 50 Hz with an amplitude of 331 V lies beyond the range of the y-axis. Excluding the fundamental amplitude allows a more detailed view of the distortions at much lower amplitudes.

Spectra for both states *PV on* and *PV off* show many similarities: In both states, the largest medians occur at odd multiples of the fundamental frequency (odd harmonics). Even harmonics have smaller amplitudes compared to odd harmonics. The presence of odd harmonic distortions is a largely discussed topic and thus not surprising [10, 52, 85]. Interharmonic content (non-integer multiples of 50 Hz) shows much smaller amplitudes compared to harmonics but is nonetheless present, especially at lower frequencies. At frequencies above 1.5 kHz, the distortions decrease both in the harmonic and interharmonic regimes. Due to the utilized Hanning window, each peak in the spectrum is represented by three neighboring components (reduced wide-range leakage at the price of increased close-range leakage [55]). The percentiles span a range above and a larger range below the medians, hinting at large variations in the distortions over the duration of the measurement. Only the measurement

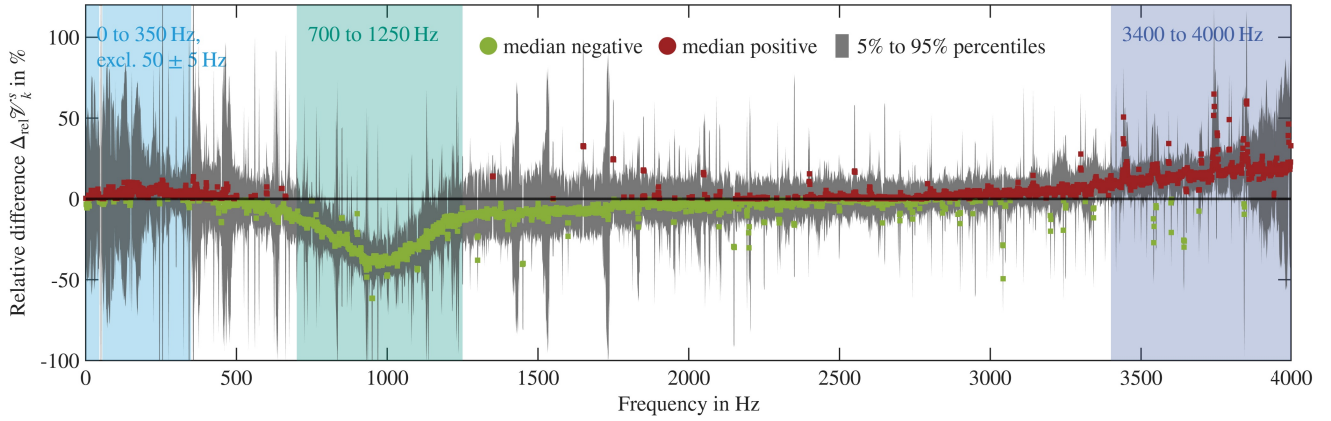


Figure 3.13: Relative change in voltage distortions due to the rooftop PV shows that the systems influence if frequency-sensitive.

of phase a in the three-phase system is discussed here. The data measured for the other phases are presented in Section A.3 and show the same characteristics.

Comparing spectra when the PV system is connected versus disconnected is challenging. In both states, the distortion profiles are similar. Only frequencies around 1000 Hz show a difference between the medians for each state. At other frequencies, the changes are small or vary from one bin to the next. Due to diverse distortions in the grid, the specific effect of the PV system is challenging to isolate.

Instead of absolute distortion spectra, Subsection 2.4.1 suggests to calculate relative differences $\Delta_{\text{rel}} \mathcal{V}_k^s$ based on distortion spectra averaged over the states *PV on* and *PV off* before and after a shutdown (see Equation 2.13). One spectrum of differences is calculated for each shutdown s . Figure 3.13 shows the median and 5 % to 95 % percentiles of the relative differences of all 80 shutdowns for each spectral bin. The median differences show both positive (red) and negative (green) values. Negative differences indicate a reduction in distortion due to the active PV system. Positive differences indicate increased distortions when the PV system is active. The majority of values lie inside a distinct frequency-dependent band. The gray percentile range encloses the band but with wider dispersion at low and high frequencies. Individual components differ from the band, for example, at 1650 Hz, including large percentile ranges. Most of these diverging components are harmonics (multiples of 50 Hz). Their absolute amplitudes are larger compared to interharmonic components (see Figure 3.12), and they are generated and altered by non-linear loads. Thus, their volatile amplitude and broad dispersion in the relative differences are as expected.

Many median differences are close to zero ($\pm 10\%$). In addition, three different frequency regions with non-zero median can be identified: There is a significant reduction in distortions between 700 Hz to 1250 Hz by more than -10% . The reductions peaks at -40% around 1000 Hz. At low frequencies (0 Hz to 350 Hz), the median is positive above 3 %, but with broad dispersion to both the positive and negative range. At frequencies between 3400 Hz to 4000 Hz the medians are positive above 10 %. However, above 3800 Hz the percentile range increases in width. At these highest frequencies, the value of the relative difference is not consistent over the different shutdowns. Figure 3.13 only includes data of one phase (phase a) of the three-phase measurement. An identical analysis for the other two phases is presented in the Appendix Section A.3. There, Figure A.5 shows that all three phases agree on the observed frequency dependence.

The 80 shutdowns are induced at different times over the course of two days (compare Figure 3.11). To investigate if the type of day (weekday versus weekend) influences the overall results, an additional analysis of both days separately is performed and presented in Section A.4 There, Figure A.7 reveals that only the relative differences in the low frequency range (0 Hz to 350 Hz) depend on the day. At all other frequencies, the results are the same on both days, especially the reduction in the medium frequency range is the same on both days.

Overall, the active PV system has a clear reductive effect on voltage waveform distortions in the medium frequency range from 700 Hz to 1250 Hz by more than 10 % and up to 40 %. In the low (0 Hz to 350 Hz) and high (3400 Hz to 4000 Hz) frequency

ranges, distortions are slightly increased due to the presence of the PV system. At all other frequencies, distortions are not affected by the system. The deeper statistical analysis in [O4] of the different frequency ranges confirms this assessment: The change in voltage distortions in the low, medium, and high frequency regions is significant, but the magnitude of the change is largest between 700 Hz to 1250 Hz. All 80 artificial shutdown events, phases, the weekday, and the weekend day confirm this behavior. The influence of the PV installation on voltage distortions is frequency-sensitive.

3.2.2 Method 2: Non-Intrusive Approach Confirms the Frequency-Dependence

Subsection 2.4.2 describes how to analyze systems that do not allow artificial switching at different times of day. This non-intrusive method exploits the switching that happens naturally during normal operation. In the morning, the system powers up once it has registered sufficient power from the solar panels, and in the evening, it shuts down. This subsection compares the results of this alternative method with those of the artificial switching presented in the previous subsection for the same rooftop PV system (described in Subsection 3.1.1). According to Subsection 2.4.2, the parameters for the non-intrusive measurement alternative have to be carefully selected for each installation separately. These parameters are the days that are included in the analysis, the extraction of the power up/shut down times, the duration of the analysis interval Δt_{ana} for which the voltage distortions are analyzed, and the time gap Δt_{gap} between the switching times and the analysis interval.

Long-term measurements over more than one year are available for the system under investigation. Only a few interruptions due to technical difficulties, device replacement, or a missing internet connection are present. The days that are included in the analysis are selected mostly due to their even distribution over the year and their inclusion of several different days of the week. To keep the amount of data manageable, two days per month are chosen, depending on the data availability in that month. The following days are included in the analysis:

Monday, 01/08/2024;	Wednesday, 01/17/2024;
Friday, 02/16/2024;	Thursday, 02/22/2024;
Friday, 03/08/2024;	Monday, 03/25/2024;
Saturday, 04/06/2024;	Thursday, 04/25/2024;
Wednesday, 05/15/2024;	Saturday, 05/25/2024;
Saturday, 06/01/2024;	Monday, 06/03/2024;
Friday, 07/12/2024;	Thursday, 07/25/2024;
Wednesday, 08/07/2024;	Sunday, 08/25/2024;
Monday, 09/09/2024;	Wednesday, 09/25/2024;
Wednesday, 10/02/2024;	Thursday, 10/24/2024;
Friday, 11/08/2024;	Sunday, 11/24/2024;
Saturday, 12/07/2024;	Wednesday, 12/25/2024;

For the current system under investigation, the power-up and shutdown times of the PV system are identified based on the power reports by inverter number three. Using a threshold on the power data is not feasible because, especially during the winter, days with very small power reports throughout a whole day are possible. Instead, switching times are defined as the first and last times at which power reports are available. The inverter only sends power reports while it is running. However, short instances of missing data during the day can occur. For example, due to network interruptions in the data report and storage pipeline. To make sure only the morning and evening switching is identified, only instances where data is unavailable for at least 4 h before the power up and after the shutdown are selected. Figure 3.14 shows the power profiles of the PV system under investigation, including the identified switching times, for an exemplary day. The power reports of all four inverters of the rooftop system are plotted. Only the power data from inverter number three is highlighted in black because the voltage

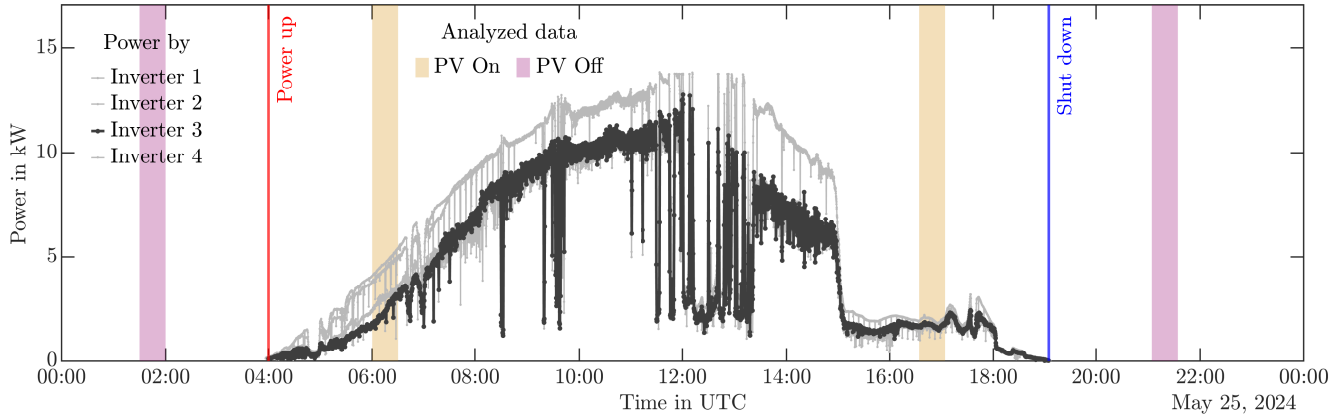


Figure 3.14: Power profile of the rooftop PV system on the 25th of May, 2024 shows the analyzed data ranges before power up in the morning and shutdown in the evening.

and current data are measured at this inverter (compare Subsection 3.1.1). The power data from the other three inverters in gray is plotted for comparison. On the 25th of May, as portrayed in the figure, the power follows a typical day profile. In the afternoon, the weather becomes cloudy, and the power output of the inverters reduces. Due to the different location, number, and orientation of the panels connected to the individual inverters (compare Subsection 3.1.1), each inverter shows an individual power profile. Figure 3.14 also shows the analyzed intervals before and after the switching, highlighted by a purple or orange background. These ranges of voltage data are included in the distortion analysis.

The time span Δt_{gap} ensures that the system is fully operational/completely shut down during the analysis interval (compare Subsection 2.4.2). As expected, Figure 3.14 shows that the power output of the inverter is very small in the early morning and late afternoon, right after power up, and right before shutdown of the PV system. Also, each of the four inverters of the system powers up/shuts down at slightly different times. This is caused by the different location and orientation of modules connected to each inverter (compare Subsection 3.1.1). To exclude any intermediate states of the system around the switching and to make sure the whole system of four inverters is fully operational/disconnected, a time gap of $\Delta t_{\text{gap}} = 120 \text{ min}$ is chosen for the analysis.

Two limitations need to be considered when selecting the duration of the analysis interval Δt_{ana} before and after the power-up/shutdown. It should be large enough to incorporate any short-term fluctuations in distortions to be a good representative of the overall distortion composition. At the same time, it should be as short as possible to reduce the amount of data that needs to be processed and thus allow a larger number of different days to be included. Figure 3.15 shows the spectrogram of voltage distortions measured on the 25th of May, 2024, one of the days included in the non-intrusive analysis. For the spectrogram, the individual spectra $\mathcal{V}_{k,\text{on/off}}(t)$ are averaged over one minute to reduce the amount of data in the visualization. According to the color bar on the right side of the figure, the spectrogram shows small amplitudes in blue, large amplitudes in yellow, and follows a logarithmic color scale. Consistently larger distortion amplitudes are visible at harmonic frequencies as lighter blue lines. Interharmonic frequencies show overall smaller amplitudes (dark and light blue regions). At high frequencies above 1.5 kHz, all amplitudes remain small (all dark blue). Shaded regions in brighter blue around 1 kHz and below 500 Hz indicate elevated distortion levels across a broad frequency range. The composition of distortion changes over the course of a day. Different frequencies follow their own dynamic: During the daylight hours from 4 to 19 o'clock UTC, when the PV system is active, distortions around 1 kHz are reduced. In addition to the day-night-dynamic, the interharmonic content around 1 kHz also regularly changes during the night. This is visible as a slight change in brightness of the blue color. Fluctuations in interharmonic content are also visible at low frequencies around 50 Hz. Their dynamics are inconsistent but generally lie below 15 min. Section A.5 shows spectrograms of several more days. These other days show the same reduction of distortions around 1 kHz during daylight hours. The variations of distortions on short time scales are either not present on other days or similar to the ones shown in Figure 3.15.

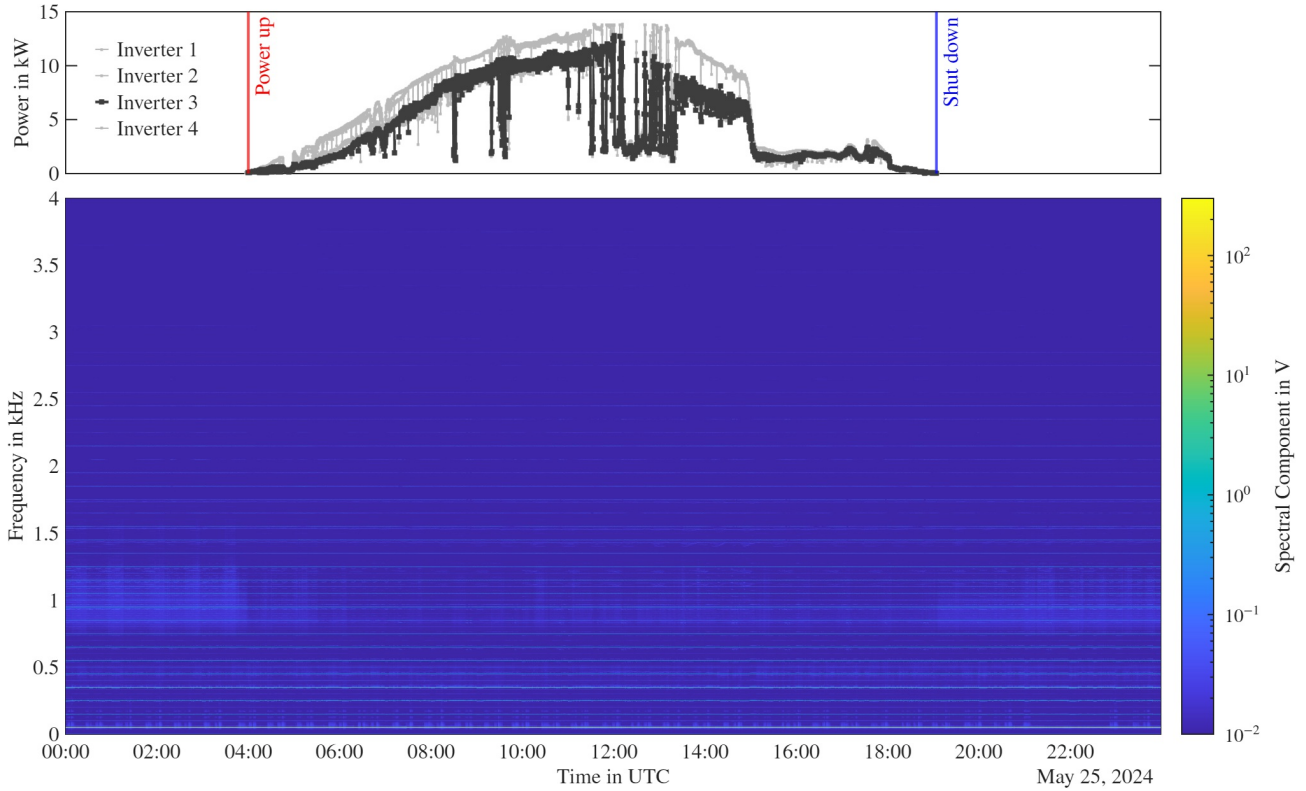


Figure 3.15: Time-series of inverter power and voltage distortion spectrogram measured at the rooftop PV system, showing reduced distortions around 1000 Hz during operation (power feed-in) of the system.

Based on the identified dynamics in the spectrum, the analysis interval is set to be $\Delta t_{\text{ana}} = 30$ min. This incorporates any short-term distortion fluctuations and thus gives an estimate of the overall distortion profile. At the same time, the amount of data is sufficiently small, the analysis is fast, and many days can be included in the analysis. The selected values for Δt_{gap} and Δt_{ana} are visualized in the power profile in Figure 3.14.

Figure 3.16 shows the median change in distortions before and after the natural switching (power up in the morning and shutdown in the evening). The analysis here focuses on the data of phase a of the three-phase voltage measurements. Figure 3.16a combines 23 power ups in the morning and Figure 3.16b results from 24 shut-downs of the PV system. On the 22nd of February, 2024, data is missing in the morning, so only the shutdown can be analyzed. Shutdown and power-up events are analyzed separately, but both show the same characteristics: The medians mainly lie in a band, with only individual (harmonic) components deviating from the overall behavior. The surrounding percentiles enclose the band but show a broader dispersion at low and high frequencies. At low frequencies, the medians are close to zero, and the percentiles span both the positive and negative range, indicating no distinct influence of the PV system on voltage waveform distortions. Around 1000 Hz the relative differences are negative down to -50% . In this frequency range, distortions are reduced during the day when the PV system is running. This was also observed in a separate analysis of normal operation data, but using other days [S1]. At high frequencies, the positive median hints at an increasing effect of the PV system on voltage distortions. However, the percentiles at these frequencies span a broad range, especially for the shutdowns in Figure 3.16b.

All of the above characteristics qualitatively agree with the results of the forced switching method described in Subsection 3.2.1. Especially, the strong reduction of distortions around 1000 Hz agrees with the results in Figure 3.13. In contrast to artificial switching, the results from the non-intrusive approach presented here in Figure 3.16 show a broader range of negative medians up to 2500 Hz. Instead, Figure 3.13 shows much smaller absolute values already at 1500 Hz. During the forced switching, this frequency region is less conclusive and rather unaffected by the PV system. In contrast to Figure 3.13, the median above 3000 Hz in Figure 3.16 changes rapidly with frequency and spans a wider range of values.

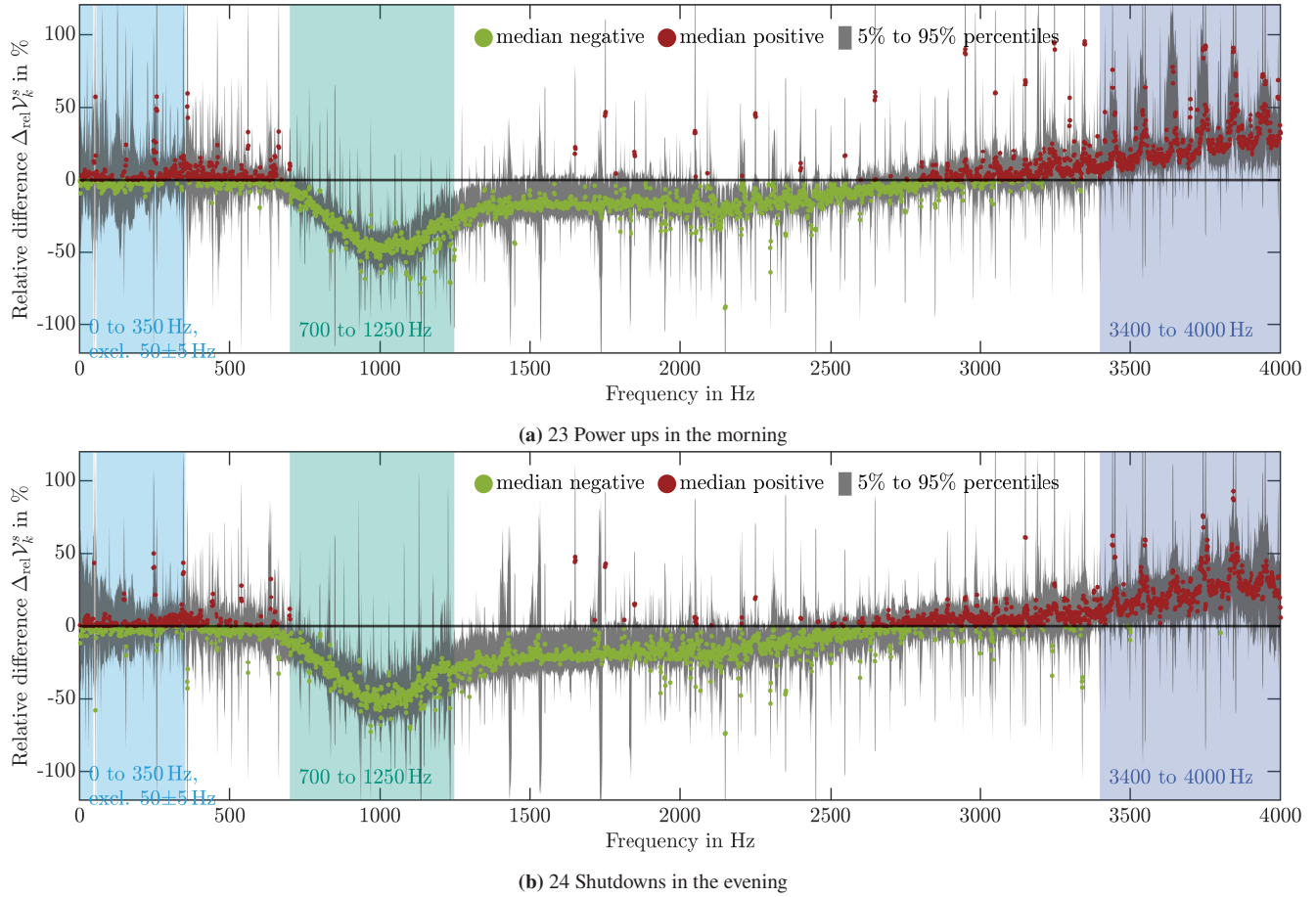


Figure 3.16: Relative change in voltage distortions due to the rooftop PV system during normal operation shows a reduction of distortions around 1000 Hz by up to -50% .

Overall, the non-intrusive characterization method shows the same reductive effect of the PV system voltage waveform distortions in the medium frequency range as the forced switching method.

3.2.3 Summary and Discussion

Voltage waveform distortions represent an important aspect of power quality, as they are associated with a variety of undesirable effects, including increased losses, equipment heating, and potential interference with communication signals. Understanding how different grid-connected components, such as loads and generators, influence these distortions is therefore of high practical relevance. In this work, a rooftop PV system was characterized with respect to its effect on voltage waveform distortions using the methodology introduced in Section 2.4. The analysis is based on repeated shutdown and startup of the system, enabling a direct comparison of distortion levels with and without the PV system connected. The results reveal a distinctly frequency-dependent influence of the PV system on voltage waveform distortions. In the medium-frequency range between 700 Hz to 1250 Hz, distortions are reduced by approximately 10 % to 40 % when the system is connected. In contrast, distortions increase at frequencies below 500 Hz and above 3200 Hz whenever the system is connected. Intermediate frequencies remain largely unaffected. Two complementary approaches were applied for characterization: controlled, induced switching at different times of day and a non-intrusive method that exploits natural transitions (startup in the morning and shutdown in the evening). Both approaches yield consistent results, demonstrating the robustness of the methodology and its applicability in real-world environments. Contrary to the commonly assumed negative influence of inverter-based resources, the present findings highlight that the PV system can, in fact, reduce voltage waveform distortions in specific frequency ranges.

The analysis benefits from several strengths. It incorporates measurements from different times of day and seasons, thereby capturing a wide range of grid conditions. The behavior is consistently observed across all three phases, at different times of day, on weekdays as well as weekends, and throughout various seasons. The agreement between induced and non-intrusive switching approaches further strengthens the validity of the results. Additionally, the large number of switching events and the consistency across all events provide a statistically robust basis for the observed trends. However, certain weaknesses must be acknowledged. The artificially induced switching analysis is limited to two days, and the overall dataset remains relatively small in terms of observation periods. In some spectral ranges, the results exhibit considerable dispersion, leading to inconclusive findings regarding whether distortions are influenced by the PV system. Furthermore, the root cause of the observed frequency-dependent behavior cannot be conclusively identified within the current analysis framework. Although relative changes in distortion levels are significant, the absolute amplitudes of many voltage distortions are small. Under present grid conditions, the influence of the PV system on the overall voltage distortion may remain small. In addition, the dependence of the observed effects on the amplitude of distortions remains unexplored, which could influence the transferability of the findings to other operating conditions. Moreover, the analysis is based on a single installation and may therefore not be representative of other systems.

Further research addresses several of the identified limitations. Section 3.3 extends the analysis to additional PV installations, improving the representativeness of the findings. A dedicated root-cause investigation is presented in Section 3.4, incorporating additional measurements and analysis techniques. Beyond the scope of this thesis, future research should focus on amplitude-dependent investigations to assess how system influence varies with distortion magnitude, as well as on expanding the dataset to include more days, seasons, and operating conditions.

In conclusion, the rooftop PV system reduces voltage distortions in the medium-frequency range around 1000 Hz, while increasing them at other frequencies. This suggests that PV systems can, under certain conditions, contribute positively to grid performance and potentially be utilized as grid-supporting elements. The influence of a PV system on voltage waveform distortions is inherently frequency-sensitive. Aggregated indicators such as THD are insufficient to capture the actual underlying effects. Instead, future analyses must maintain a high spectral resolution to fully account for the complex frequency-dependent characteristics. The presented methodology proves to be capable of capturing these effects with high resolution and attributing them to a specific component within the complex and dynamic environment of a public distribution grid.

3.3 Comparison: Different Influence on Voltage Distortions for Each Photovoltaic System

The previous Section 3.2 applied the new field-measurement method presented in Section 2.4 to a rooftop PV system. Both the robust induced-switching methodological approach that relies on forcing the system to shut down at different times of day, as well as the non-intrusive alternative that exploits the normal switchings (power up in the morning and shut down in the evening), are used on the same system. It was found that the change in voltage distortions that occur when the system is disconnected from the grid is frequency sensitive. Explicitly, the system reduces distortions around 1000 Hz while increasing them at lower and higher frequencies. However, the behavior of this one PV system cannot automatically be transferred to other systems; in fact, their characteristic influence on voltage distortions might look completely different. To assess how PV systems differ in their behavior, this section applies the new method to two more systems. First, Subsection 3.3.1 uses the induced-switching approach to characterize the SYSLAB system described in Subsection 3.1.2. Because the laboratory system can operate both connected to the public grid as well as in an isolated microgrid formed by a grid emulator, its behavior in different grid settings is evaluated. Afterwards, Subsection 3.3.2 applies the non-intrusive alternative to characterize the large PV field presented in Subsection 3.1.3. The measurements will also be included in a publication currently being drafted.

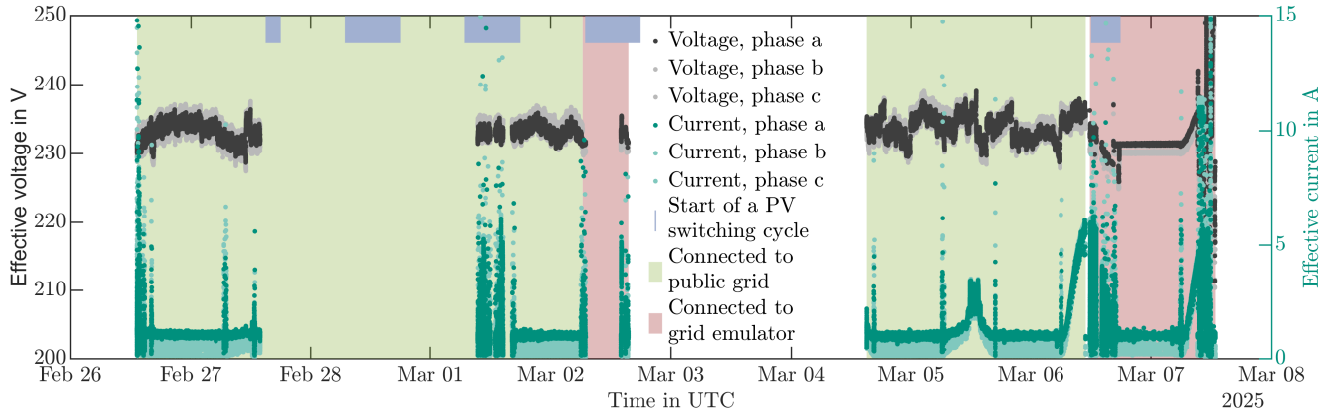


Figure 3.17: Current and voltage measured at the SYSLAB PV system in two different grid states (public grid versus grid emulator).

3.3.1 SYSLAB Photovoltaic: Connected Grid Majorly Determines the Behavior of the System

Subsection 3.1.2 describes another PV system that was investigated in the course of this thesis. This second system is located in Denmark at the SYSLAB of the DTU, and the data was acquired in parallel to experiments related to another project (compare Subsection 3.1.2).

The experiments lasted from the 24th of February, 2025, to the 7th of March, 2025. The lab to which the PV system is connected allows two different grid configurations: Connection to the public grid or to a grid emulator. The underlying Whiplash experiments investigate potential impacts of cyber attacks on inverter-based resources (PV, battery inverters). Two different types of PV shut-downs occur during the experiments: Actively induced switching by controlling the circuit breaker connecting the system to the rest of the lab, and emergency shutdowns of systems as a result of the attack. The EDR was connected from the 26th of February at noon to the 7th of March at noon to record voltages and currents on all three phases.

Figure 3.17 gives an overview of available data. The y-axis on the left side shows the effective grid voltage in black, and the right y-axis refers to the effective inverter current in green. Both the effective voltage and current values are feature data reported by the EDR (see Section 2.1). The recorded current values are divided by three before being plotted here because the Rogowski coils were wrapped around the measurement point three times and thus record three times the actual current flowing through the line (compare Subsection 3.1.2). The figure also highlights the different grid configurations under which the system is operated. Most of the time, the public grid (green regions) is connected. On the 2nd and 7th of March, the PV system is operated under the grid emulator (red regions). Voltage measurements vary between 230 V and 240 V in the public grid configuration. In the grid emulator configuration, while no cyber attacks are run and the PV system is inactive (between 6th of March 6 pm and 7th of March 7 am), the effective voltage has a constant Root Mean Square (RMS) over time of 230 V. Due to the overall cloudy weather, only very small inverter currents are measured most of the time. In contrast, individual large currents are reported, mostly around the induced switching cycles. Short vertical blue lines located at the upper x-axis in Figure 3.17 mark the starting points of PV switching cycles. Due to the large number of cycles, the lines appear as broader regions. Each switching cycle includes the following steps: A new cycle starts every 7 or 10 min. First, the inverter is instructed to shut down. 5 s later, the circuit breaker between the PV system and the rest of the laboratory is opened. After 4 min of disconnection, the PV system is reconnected and powered up. After another 3 or 6 min, the next cycle starts. Several cycles were run on several days. On the 7th of March, additional drops in the inverter current are visible that do not coincide with switching cycles. These shutdowns are a result of emergency shutdowns during the tested attacks (see the following Figure 3.18 for the time range of these switchings). Both types of switching (active switching cycles or protection shutdowns during attacks) are included in the analysis.

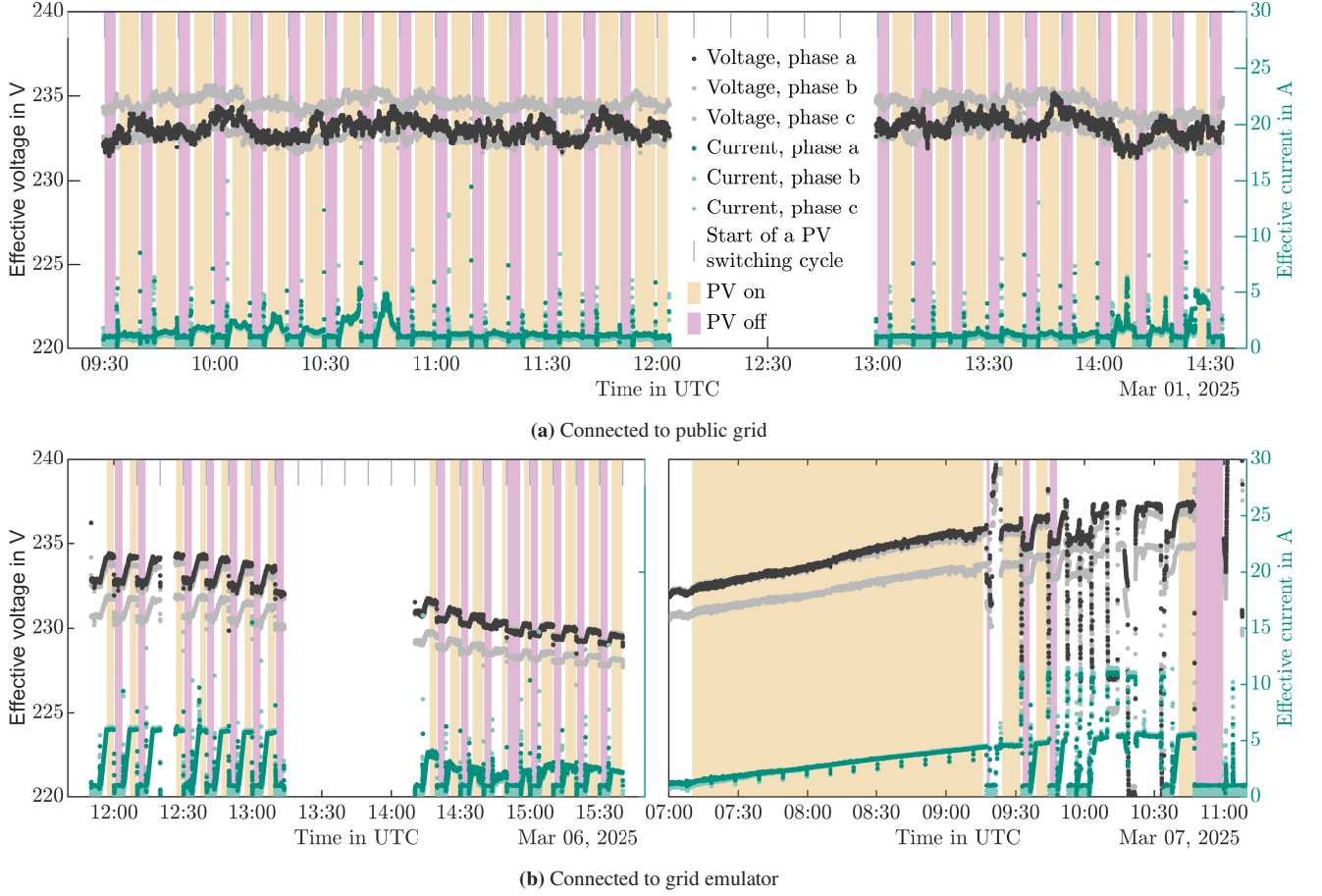


Figure 3.18: Current and voltage measured during switching operations at the SYSLAB PV system. Orange and purple data regions are included in the distortion analysis.

In accordance with Subsection 2.4.1, the first step is the spectral analysis of all available voltage data based on the algorithm described in Subsection 2.2.2 towards voltage distortion spectra $\mathcal{V}_k(t)$. In the next step, the switching times of the PV system have to be identified to be able to separate the states *PV on* and *PV off*. Figure 3.18 shows zooms into the switching time ranges in Figure 3.17. The data is separated into ranges where the PV system is operated in the public grid (Figure 3.18a) and operation under the grid emulator (Figure 3.18b). The switchings in the right-hand plot in Figure 3.18b are not caused by intended switching cycles (marked by blue vertical lines on the upper x-axis in the other plots) but occur due to protection shutdowns as a result of the tested cyber attacks. Each of the switching events shows large peaks in the current both around power-up and shut-down. The operation of the circuit breaker likely causes these peaks. The inverter power linearly ramps up to its maximum for several minutes (3 min) after powering up. As a result, only shutdown events are considered because they have a small time lag between the states *PV on* and *PV off*. The data ranges around the switching that are included in the analysis are carefully selected to ensure high data quality. Only events with sufficiently long (more than 1 min) of representative data on either side of the shutdown are included. Data ranges with voltage and/or current peaks and/or transients due to the switching or cyber attacks are excluded. Figure 3.18 highlights the selected data ranges: Orange data regions when the PV system is running (state *PV on*) and purple data regions when the PV system is shut down (state *PV off*). These data ranges are included in the following distortion analysis.

The individual distortion spectra $\mathcal{V}_{k,on/off}(t)$ are assigned to the states *PV on* and *PV off* as well as the grid configuration (public grid versus grid emulator). Figure 3.19 shows the voltage distortion spectra for all four different states. Figure 3.19a compares the median of distortions during all orange data regions in Figure 3.18a (*PV on*, connected to public grid) with those of all purple data regions (*PV off*, connected to public grid). 5 to 95 percentiles are also shown. In both states (*PV on* and *PV off*), the voltage has high median distortion amplitudes at harmonic frequencies and smaller amplitudes at interharmonic

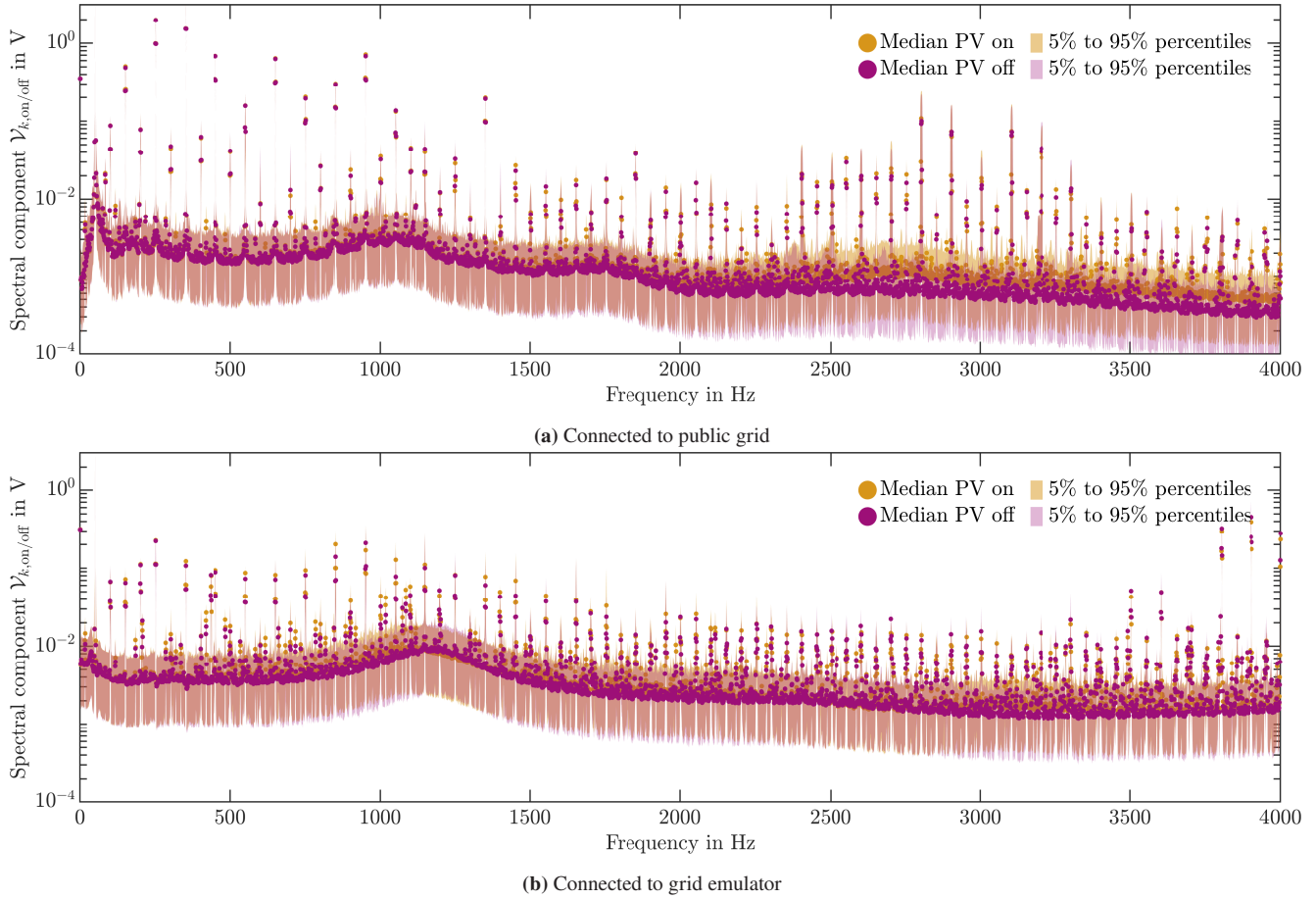


Figure 3.19: Voltage distortions at the SYSLAB PV system. The two grid configurations have different voltage distortion compositions.

frequencies. Comparing the orange (*PV on*) and purple (*PV off*) spectra, differences are only visible at higher frequency components, where distortions are larger when the PV system is connected. An identical visualization of distortions during operation under the grid emulator (time ranges in Figure 3.18b) is shown in the lower Figure 3.19b. Again, harmonic distortion amplitudes are larger compared to interharmonic amplitudes. No clear differences between distortions in states *PV on* and *PV off* are visible.

The distortion composition of the grid emulator voltage is different from that of the public grid. For example, at 1200 Hz, the interharmonic distortions have larger amplitudes in the grid emulator data compared to public grid data at the same frequency. The root cause of these differences is difficult to deduce. Both grid configurations represent a complex system. And the information on the different loads and generators in the grids is limited. This is true even in the grid emulator configuration: While the names and interconnection of components are known, their impedance characteristic, as well as control/switching-related contributions to voltage distortions in the grid, remain unknown. In the case of public grid configuration, naturally, even less information is available. However, the difference in voltage distortion composition shows that the two different grid configurations represent two distinguishable grid situations. Due to the multitude of distortion amplitudes and a broad range of percentiles, the influence of the PV system in each grid configuration is difficult to discern in the absolute distortion spectra.

To highlight the effect of the PV system, the individual distortion spectra $\mathcal{V}_{k,on/off}(t)$ are averaged (mean) over each state *PV on* or *PV off* separately in accordance with Subsection 2.4.1. These aggregation intervals have different lengths, depending on the duration of the state (compare highlighted data regions in Figure 3.18). Afterwards, the relative difference for each shutdown is calculated based on Equation 2.13. Figure 3.20 presents the median and percentiles of differences over all shutdowns, separated into 23 shutdowns during operation in the public grid and 18 under the grid emulator. When connected to the public

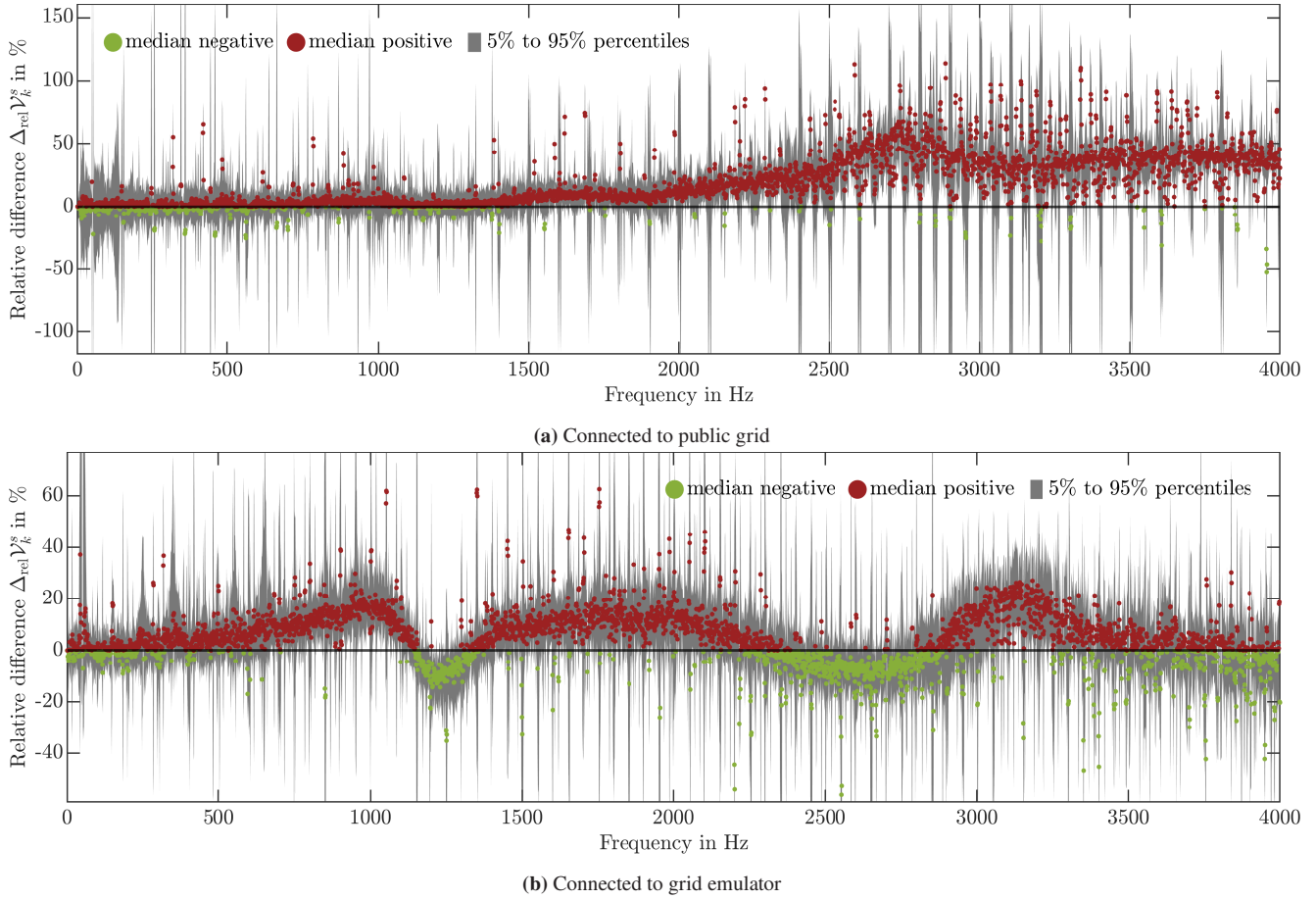


Figure 3.20: Relative change in voltage distortions due to SYSLAB PV system. The influence of the system on voltage distortions depends on the grid configuration.

grid in Figure 3.20a, the disconnection of the PV system causes increased distortions at frequencies above 2000 Hz. This was already observed in Figure 3.19a and is here visible as positive differences. At all other frequencies, the differences are close to zero, and the percentiles span both the positive and negative frequencies. In other words, the PV system has no significant influence on voltage distortions below 2000 Hz. While the PV system is operated under the grid emulator (Figure 3.20b), the frequency dependence looks quite different: Around 1250 Hz and between 1300 Hz and 2800 Hz, the PV system has a reductive influence on voltage distortions (negative medians and a narrow range of percentiles). At other frequencies (500 Hz to 1100 Hz, 1400 Hz to 2200 Hz, and 3000 Hz to 3300 Hz), distortions are larger when the PV system is connected. Whether the influence is reductive or increasing depends on the frequency. At all frequencies, the effect is small (below 40 %) compared to the influence in the public grid (up to 100 % at several frequencies around 2750 Hz).

Overall, the influence of the PV system on voltage waveform distortions has an individual characteristic in the different grid configurations (public grid versus grid emulator). Whether the PV system increases, decreases, or does not affect a voltage distortion at a certain frequency depends on the connected grid configuration. In addition, the influence on the public grid voltage distortions is different compared to the first system under investigation (compare Subsection 3.2.1). To further investigate this variety of PV system-related changes in voltage distortions, the following subsection analyzes measurements taken at a third system.

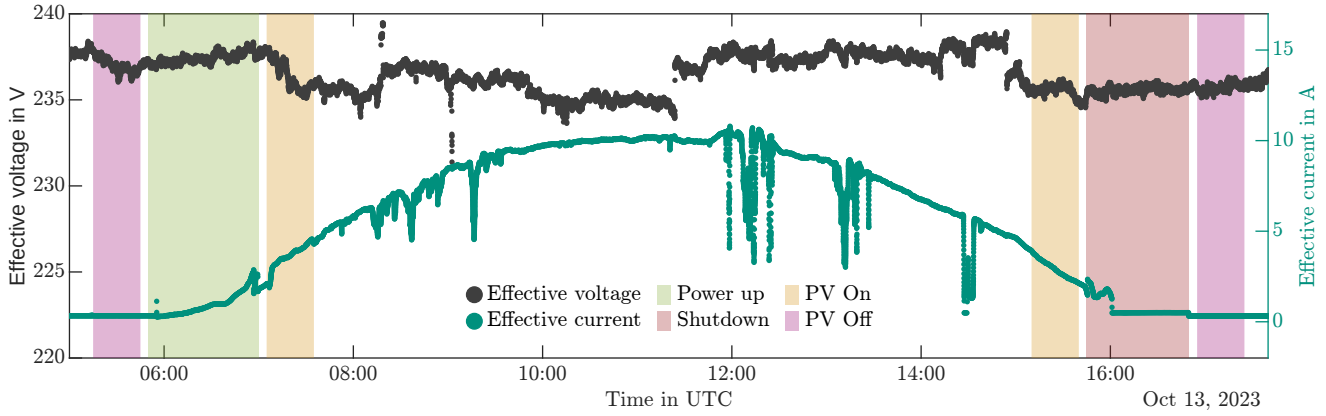


Figure 3.21: Current and voltage measured at the PV field and identified regions during which the system switches between the states *PV on* and *PV off*.

3.3.2 Photovoltaic Field: Another Distinct Frequency-Dependent Change in Voltage Distortions

Subsection 3.1.3 describes a large PV field that was characterized in the course of this thesis. Same as for the systems discussed before, its influence on voltage waveform distortions is of interest, but, for this system, no artificial switching is possible due to limited access: Neither a network connection to the inverter nor long-term physical access to the switching box was available. Instead, the alternative non-intrusive approach presented in Subsection 2.4.2 is applied. The influence of the system was investigated by comparing day and night data. All measurements were performed between the 11th of October, 2023, and the 17th of February, 2024. Instead of piping data online to the large data storage (see Section 2.1), the data was stored on portable hard drives because no internet connection was available in the field.

According to the method description in Subsection 2.4.2 and its application to a different system in Subsection 3.2.2, several choices have to be made before the analysis: Which days should be included in the analysis? How can the switching times be identified? How long should the analysis interval Δt_{ana} be? How large should the time gap Δt_{gap} be between the switching times and the analyzed intervals?

The following days are included in the analysis:

Wednesday, 10/11/2023 [↘] ;	Sunday, 10/22/2023 [↗] ;
Friday, 10/13/2023;	Sunday, 12/03/2023;
Sunday, 10/15/2023;	Friday, 02/02/2024;
Monday, 10/16/2023 [↗] ;	Monday, 02/05/2024;
Tuesday, 10/17/2023;	
Wednesday, 10/18/2023 [↗] ;	
Thursday, 10/19/2023 [↗] ;	↘ Only shutdown investigated;
Saturday, 10/21/2023;	↗ Only power-up investigated

The days are selected based on data availability and data quality. In addition, days with very cloudy weather and thus very small current feed-ins are excluded, because the switching times are difficult to differentiate on these days.

Figure 3.21 shows the 1 s feature data provided by the EDR (compare Section 2.1) on an exemplary day. Explicitly, the measured effective voltage and current of phase a of the three-phase measurement on the 13th of October are presented. The voltage in black depicted on the left axis has values around 235 V. All switching times (power up in the morning and shut

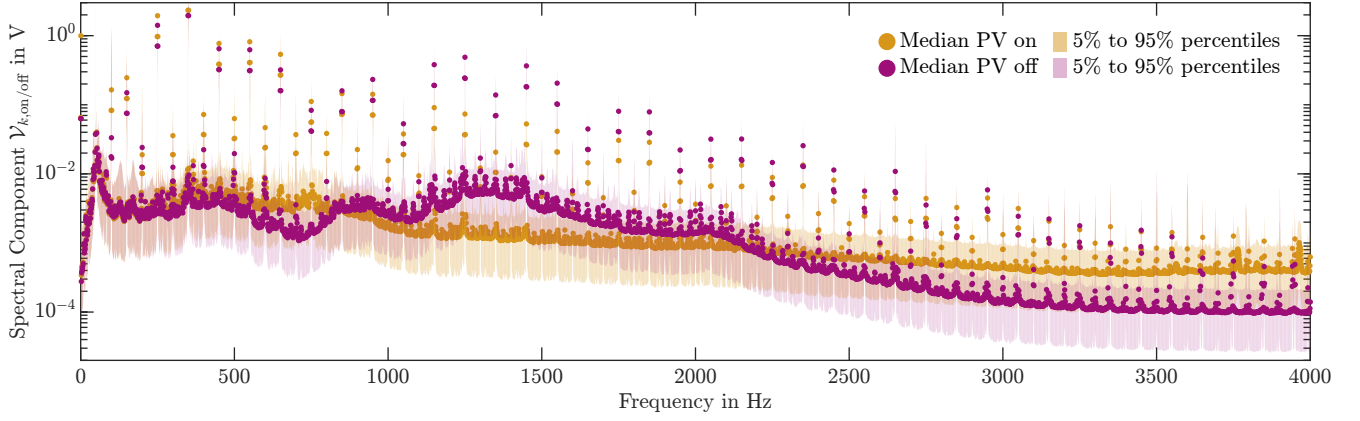


Figure 3.22: Voltage distortions at the PV field are different during the night compared to daytime, when the PV system is connected.

down in the evening) are determined based on the inverter current measurements in green on the right axis. The current follows a typical day profile: In the morning, the current gradually increases, reaches its maximum around midday, and decreases towards the evening. At several points in time, small drops in the current are visible. These could be caused by short-term shading of the system, for example, due to clouds. During the night, a very small (but non-zero) current of 0.3 A is recorded. At the end of the day, before dropping to this nighttime level, the current amplitude remains at a constant value of 0.5 A for about 50 min. This means intermediate states are possible during the switching process, before the system is fully powered up or shut down. They should be excluded from analysis to focus on the influence of the PV system during normal operation. So instead of identifying a singular point in time as the power-up/shutdown, a time interval during which the power-up/shutdown occurs is selected. Figure 3.21 highlights the identified switching intervals for the shown day. Any intermediate states, as well as times with very low current measurements (low power feed-in), are included in the power-up/shutdown intervals. The start and end times of these intervals are identified based on the current measurement in Figure 3.21 and similar zooms around the other selected days. It is not possible to automate the switching interval detection based on thresholds because the current is non-zero during the night, and similar small currents can occur during the day due to the weather.

The duration of the analysis interval is selected to be $\Delta t_{\text{ana}} = 30$ min. This reduces the amount of data that has to be analyzed. The analysis intervals of data are separated from the start/end of the switching interval by a gap of $\Delta t_{\text{gap}} = 5$ min. As the regions of switching identified in Figure 3.21 already include volatile, intermediate states, or low-power regions around the switching, the analysis interval does not need to be separated further from the switching intervals. The selected time gap and analysis interval are also visualized in Figure 3.21 as orange and purple data regions.

The waveform components of $\Delta t_{\text{ana}} = 30$ min of voltage data on either side of the power-up/shutdown are extracted using the analysis described in Subsection 2.2.2. This results in a time series of voltage distortion spectra $\mathcal{V}_k(t)$ (one for each second). Figure 3.22 compares these voltage distortions between day- and nighttime measurements (before/after shutdown/power-ups). The figure shows the median and percentiles of all spectra $\mathcal{V}_{k,PV\text{ on}/PV\text{ off}}(t)$ but separated into states when the system is running (*PV on*, daytime) versus when it is not running (*PV off*, nighttime). The spectra both show the same overall characteristics already observed in Figure 3.12: Harmonic voltage distortions are larger compared to interharmonic components. The distortion amplitudes decrease with frequency. The percentiles span a large range around the median, hinting at large changes in distortion composition from one spectrum to the next. Comparing the median of all nighttime data (without PV) and daytime data (PV connected), the difference between the PV system being active vs inactive is apparent. Between 600 Hz and 800 Hz, as well as above 3000 Hz, the distortion amplitudes are larger during the day. Between 800 Hz and 2200 Hz, distortions are reduced during the day compared to nighttime measurements.

Figure 3.23 shows the relative differences between the distortions before and after power-up/shutdown of the PV system in accordance with Equation 2.13. The spectra during each individual analysis interval were aggregated (mean) into one representative spectrum for the state. Power-ups and shutdowns are analyzed separately. The median relative differences of all

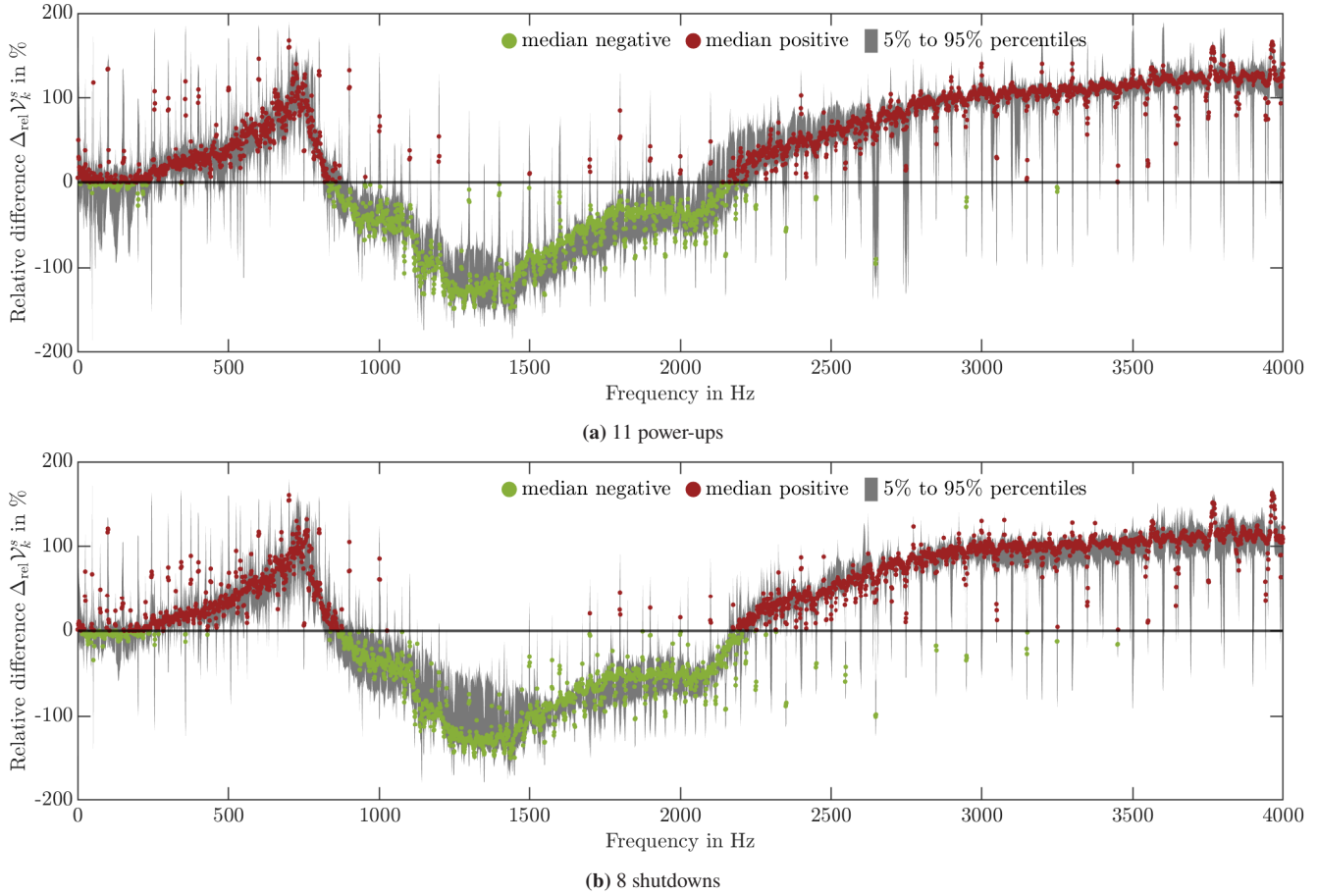


Figure 3.23: Relative change in voltage distortions due to PV field shows a distinct frequency-dependence that is different compared to other systems.

11 power-ups in Figure 3.23a show the same characteristics already observed in the absolute spectra in Figure 3.22: Between 800 Hz and 2200 Hz, the differences are mostly negative because distortions are reduced due to the PV system being connected during the day. From 600 Hz to 800 Hz, as well as above 3000 Hz, the differences are positive, and distortion amplitudes are larger during the day with the PV system. The percentiles span a narrow range around the medians; similar relative differences are calculated at each power up. The median differences of the 8 shutdowns in Figure 3.23b show the same characteristics. The influence of the PV system on voltage distortions is frequency sensitive. Both the data around power-ups and shutdowns confirm this.

Overall, a characteristic influence of the PV system on voltage waveform distortions is detected. The characteristic differs from the other two investigated systems. For example, the frequency range where distortions are reduced is much broader compared to the influence of the rooftop PV system presented in Subsection 3.2.1.

3.3.3 Summary and Discussion

Previous results in Section 3.2 demonstrated that the influence of a rooftop PV system on voltage waveform distortions is strongly frequency-dependent. However, given the wide diversity of PV installations, conclusions drawn from a single system cannot be generalized. Different system configurations, inverter technologies, and grid conditions might lead to very different influences on voltage distortions. To address this, the present section extends the analysis to additional systems using the same field measurement method introduced in Section 2.4. The PV system installed in a laboratory in Denmark was investigated using the induced switching approach. It shows a different behavior compared to the rooftop system, with

almost no observable influence on voltage waveform distortions in the public grid below 2500 Hz. In addition, the analysis of a large PV field using the non-intrusive method reveals yet another distinct spectral characteristic. Furthermore, the laboratory system was also examined in an alternative grid setting. When operated under a grid emulator instead of the public grid, it shows a pronounced frequency dependence with reductions in several frequency ranges. These findings clearly indicate that the influence of PV systems on voltage distortions is not only frequency-dependent but also system-specific and depends on the connected grid. These findings have several important implications: First, they confirm the suitability of the presented field measurement method for analyzing real-world systems under varying conditions and levels of accessibility. At the same time, they highlight the strong individuality of PV system behavior: Each installation must be characterized separately. The non-intrusive approach is particularly valuable in this context, enabling the investigation of systems where impairment of operation is not possible. More broadly, the results demonstrate that the combined system of the PV installation and its connected grid must be considered as a whole, as their interaction determines the observed effects. In cases where the grid dominates the overall behavior, the influence of the PV system may not be detectable at all.

A key strength of this study lies in the consistent application of the same analysis methodology to all investigated systems, enabling a reliable comparison of results. For each system, the observed behavior remains stable across a large number of data points, as evidenced by narrow distributions and consistent trends. The inclusion of the same system under different grid conditions further highlights the role of the grid in shaping the observed effects. Additionally, the successful application of the non-intrusive approach to the PV field demonstrates its practical value, particularly for systems where direct intervention or controlled switching is not feasible. Nevertheless, several challenges and limitations affect the investigations. As discussed in Subsection 2.4.3, restricted data availability can limit statistical robustness. In practice, measurement campaigns are often constrained by limited access to systems, interruptions in data acquisition, and varying data quality. These factors are inherent to real-world investigations of commercial installations. Moreover, if no direct power measurements are available, determining the operational state of a system can be difficult. For example, the current draw during standby operation may be difficult to distinguish from the current feed-in at low-power generation. The different number of switching events across systems results in varying levels of statistical confidence. A lower number of switching events increases the likelihood that external grid influences are not fully averaged out. Even though the investigated systems already cover a large variety of power levels and inverter manufacturers, the number of investigated systems and grid configurations remains small relative to the vast diversity of real-world installations. Finally, the underlying physical mechanisms driving the observed frequency-dependent effects, as well as their dependence on grid characteristics, remain unresolved.

Future work might aim to expand the datasets by including a larger number of systems and increasing the duration of measurement campaigns to improve statistical significance. A broader analysis across many installations would also help quantify how frequently PV systems exhibit a measurable influence compared to dominant grid effects.

In conclusion, the presented results demonstrate that the influence of PV systems on voltage waveform distortions is not only frequency-dependent but also highly installation-specific and strongly influenced by the connected grid configuration. The same PV system may exhibit different behavior when connected to different grids; the system and the grid together are a coupled entity. The field measurement method developed in this thesis provides an effective means to capture this behavior on a case-by-case basis. Building on these findings, the following section investigates the root causes of the observed characteristics through additional measurements and analysis.

3.4 Root-Cause Analysis: Grid-Side Hardware Filter is Primarily Responsible

The method presented in Subsection 2.4.1 and its application in Subsection 3.2.1 show that the rooftop PV system has a frequency-sensitive influence on grid voltage waveform distortions. Depending on the distortion frequency, the effect is reductive, increasing, or inconclusive. This section investigates possible root causes of the measured dependence. Knowledge of the root cause of an effect allows one to predict the behavior in different configurations or other systems.

One root cause for changes in voltage distortions are the multitude of other nonlinear loads and generators connected to the public distribution grid. They each influence the voltage distortion composition in their own individual way. Any one of these components in the grid could be responsible for changes in voltage distortions from one point in time to the next, either by them disconnecting or reconnecting to the grid or changing their operating state. However, the measurement method developed in this thesis makes it extremely unlikely that any load or generator other than the system under investigation is responsible for the observed changes in voltage distortions. The system under investigation is the only change consistent over the multitude of switching operations conducted during the experiments.

Up to this point, an overall system-wide view on PV installations was maintained without considering the multitude of components included in the system (PV modules, their interconnection, the PV inverter with filters, switching circuit, and control, etc.). For the present root-cause analysis, the potential roles of different PV system components must be differentiated. A special focus is laid on the PV inverter in this thesis, as it presents the two most likely root causes of the observed frequency-dependence.⁴ The control algorithms of the inverter are the first prominent candidate to cause the change in voltage distortions. An inverter's control uses switching operations to generate the required sinusoidal output current from the DC voltage supplied by the PV panels. This includes maximizing the power output based on the available voltage-current characteristics of the solar panels. The influence of control algorithms is primarily observed at individual frequencies (frequencies of control and harmonics thereof) and often changes with operating point and thus power output of the device.

The second candidate for the behavior is the passive circuit components in the inverter, specifically the output (grid-side) filter of the PV system. This filter is installed to smooth the switching-related ripple of the current signal. By filtering the high-frequency switching, the inverter current better approximates the intended sinusoidal waveform. Such grid-side filters have a broad frequency response which will affect the measurements over a wide frequency range. Therefore, the measurement results clearly differentiate them from single-frequency harmonic injections. In addition, the filter response is passive and will not depend on power.

To evaluate these potential root causes for the observed frequency-dependence, several additional measurements and analyses performed for the rooftop PV system are presented. These are the measurements of the frequency-dependent impedance with and without the PV system connected in Subsection 3.4.1, investigation of power dependence of voltage distortions in Subsection 3.4.2, and a comparative analysis of grid voltage and inverter current distortion phase angles in Subsection 3.4.3.

3.4.1 Additional Measurements: Change in Grid Impedance Due to Activation of PV System

The grid impedance determines how much a current injection affects the grid voltage. Therefore many studies include the frequency depended grid impedance Z into investigations on power electronic devices [86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96]. The grid side filter influences the inverter impedance [97].

This subsection investigates whether and how the rooftop PV system (described in Subsection 3.1.1) changes the measured grid impedance at its connection point. Additionally to the measurements presented in Section 3.2, impedance measurements are performed on the same system. These measurements use the ONIS impedance spectrometer by the company morEnergy [98]. It is installed at the connection point of the PV system (the same point where the EDR device is connected). The ONIS device measures the impedance over a large range of frequencies by applying a specialized excitation signal at the point of measurement. Both the magnitude and phase angle of the complex impedance are recorded. The impedance between each phase and the neutral conductor is estimated separately, one after the other. All impedance measurements were performed on one individual day, the 16th of December, 2024. The battery system installed in the vicinity of the rooftop PV system is disconnected throughout the impedance measurements (see also Subsection 3.1.1).

⁴ Special thanks to the exchanges with several experts that helped collect and narrow down the potential root causes. These include Prof. Dr.-Ing. Marc Hiller, Dr.-Ing. Richard Jumar, M.Sc. Dominik Schulz, Dr.-Ing. Rüdiger Schwendemann, and an anonymous reviewer for the International Journal of Electrical Power and Energy Systems.

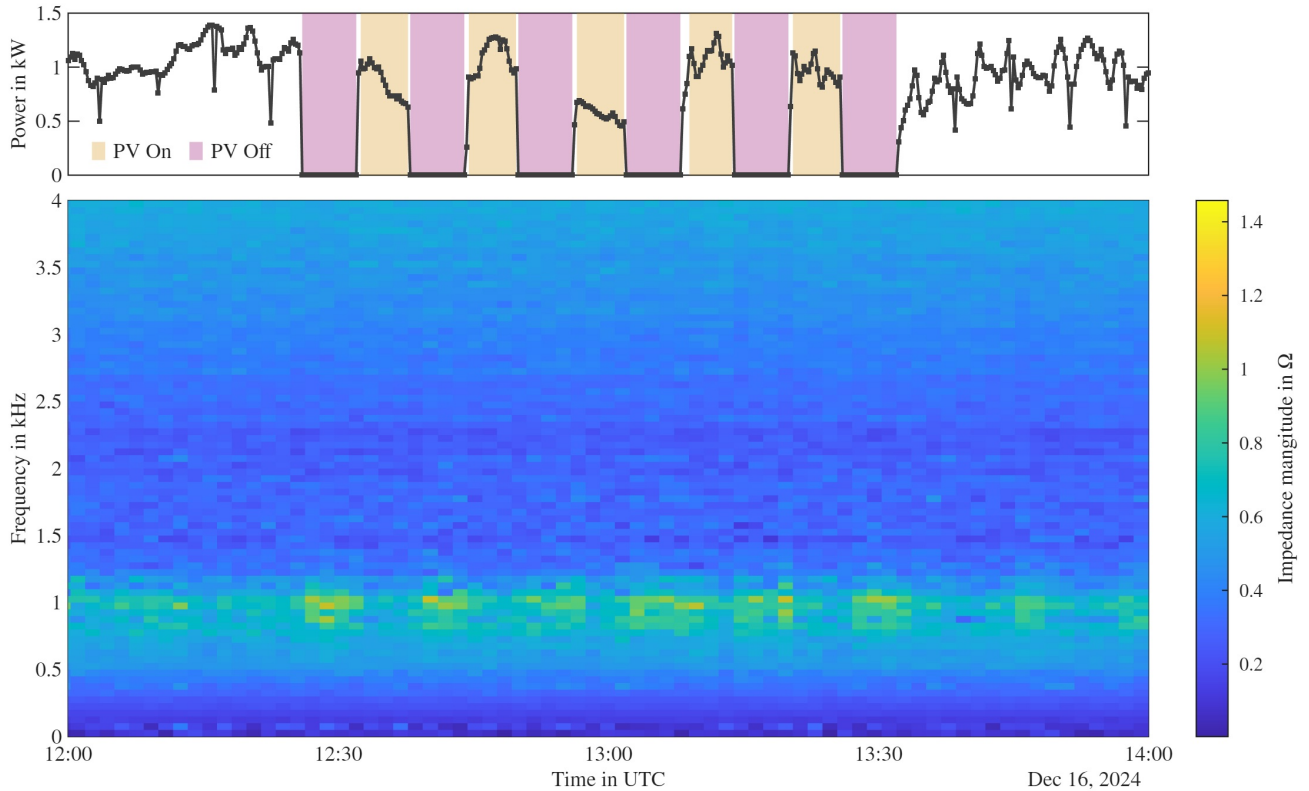


Figure 3.24: Impedance spectrogram measured at the rooftop PV system shows reduced impedance magnitude around 1 kHz whenever the system is connected to the grid (see power time series in the upper plot).

The impedance measurements are regularly repeated over the course of several hours.⁵ In parallel, the PV system is repeatedly switched on and off, following an automated switching schedule. Starting at 12:26, the PV system is powered down for 5 min and powered up for 7 min several times until 1:30 pm. The switching implementation and power reports work the same as described in Subsection 3.2.1.

Figure 3.24 gives an overview of the impedance data acquired during the measurement. The power reported by inverter number three of the PV system in the upper plot shows the dis- and reconnection as repeated drops to zero power. Measured impedance magnitudes of phase a are depicted as a spectrogram in the lower plot. The shown frequency region is reduced to the same region investigated in the field measurement (up to 4 kHz). Around 1 kHz, the impedance attains its highest values within the depicted frequency range. The magnitudes are smaller at lower and higher frequencies, but show a slight increase towards the highest displayed frequency. The switching of the PV system is also visible in the impedance spectrogram at frequencies around the peak at 1 kHz. When the system is inactive, the peak reaches higher values. For each individual state, the impedance remains relatively stable, making the switching times clearly identifiable in the spectrogram.

Instead, the start and end of the states *PV on* and *PV off* are extracted by hand as the first and last data points at which the system is completely running/shutdown. These time ranges are highlighted in the upper plot in Figure 3.24. Depending on their time of measurement, the impedance spectra are assigned to the states *PV on* and *PV off*, similar to the analysis of voltage spectra described in Subsection 2.4.1. The impedance spectra are aggregated (median and percentiles) separately for each state. As a result, an overall impedance characteristic for each state of the system (with and without the PV system connected) is available.

⁵ The following measurement parameters are set in the impedance spectrometer: Number of cycles: 5; phase combinations: 11_n, 12_n, 13_n; minimum frequency: 0; maximum frequency: 500000; minimum pulse frequency: None; maximum pulse frequency: None; interval: 30, enable sub cycle: Off; save signal to file: Off, interval: 30. The interval of 30 s is the pause between two consecutive measurement cycles. Each measurement cycle takes a few seconds, including the investigation of each phase separately.

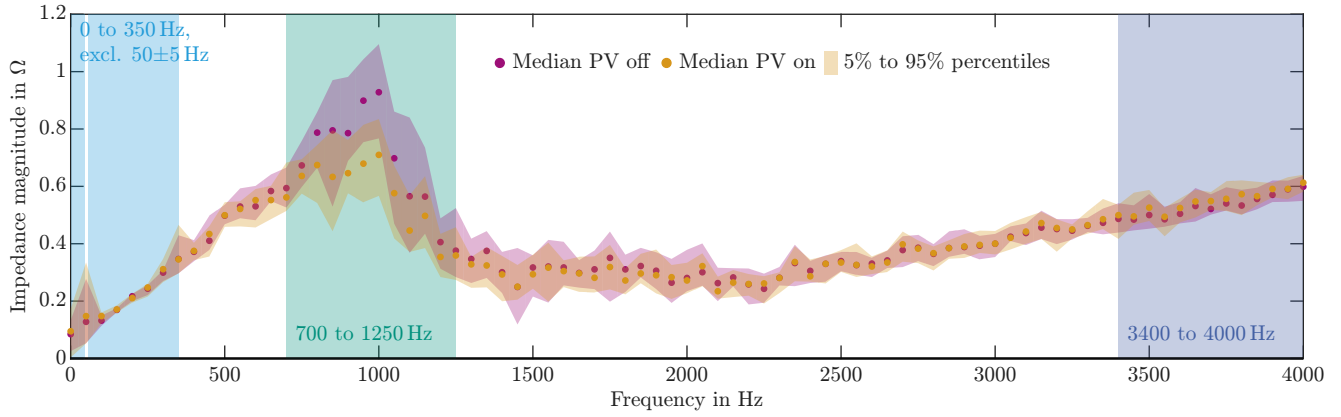


Figure 3.25: Impedance magnitude with and without rooftop PV system connected to the grid shows a reduced magnitude around 1000 Hz whenever the system is connected.

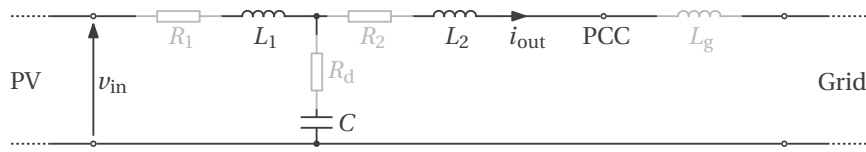


Figure 3.26: Circuit diagram of LCL filter between PV inverter and the grid. Diagram similar to [101, 102, 103].

Figure 3.25 shows the median and percentiles of 21 impedance magnitude spectra during disconnected and 15 spectra during active PV system. The impedance without the PV system connected, shown in purple, is the impedance of only the public grid. With the system connected, the impedance changes to the orange data. The overall characteristic visible in the spectrogram in Figure 3.24 is also apparent here: The impedance magnitude has a peak around 1000 Hz. At lower and higher frequencies, the magnitude is smaller, but increases again towards 4000 Hz. The percentiles span a range around the data with larger dispersion at the peak around 1000 Hz. At other frequencies, the impedance characteristics are very similar at all measurement points, visible in the narrow percentiles around the median. This is true for both states *PV on* and *PV off*. The peak amplitude is reduced when the PV system is connected. This influence of the system on the grid impedance occurs at the same frequency region where alterations in the voltage distortions were observed in Subsection 3.2.1 and Subsection 3.2.2. In addition to the impedance of phase a in Figure 3.25, Subsection 4.2.2 analyzes the impedance measurements of the other two phases b and c. While the impedance around 1000 Hz is the same in all three phases, the impedance magnitude of phase a is smaller in phase a compared to the other two phases at frequencies above 2000 Hz.

The grid impedance is visibly reduced over a broad frequency region around 1000 Hz whenever the PV system is connected. This alteration over a broad frequency range hints at an underlying filter effect. Inverters, as part of the PV system, have grid-side filters that smooth the switching-generated output current to better approximate the intended sine wave. The inductor-capacitor-inductor (LCL) filter design is chosen because it allows strong suppression at the high inverter switching frequencies [99]. However, they come with the challenge of a resonance peak at lower frequencies [100].

The circuit diagram of an LCL filter is shown in Figure 3.26. It converts the input voltage v_{in} on the inverter side, resulting in an output current i_{out} through the Point of Common Coupling (PCC) between the PV system and the grid. An LCL filter corresponds to a combination of two inductances L_1 and L_2 and a filter capacitor C . On the grid side, another inductance L_g is included that represents the inductance introduced by other loads and generators in the grid. Additional components or non-idealities of the components can also be present. These are a damping resistor R_d in parallel to the capacitor, or resistances $R_{1/2}$ in series with $L_{1/2}$. They are included in gray in Figure 3.26 but are not considered in the following filter transfer function for simplicity.

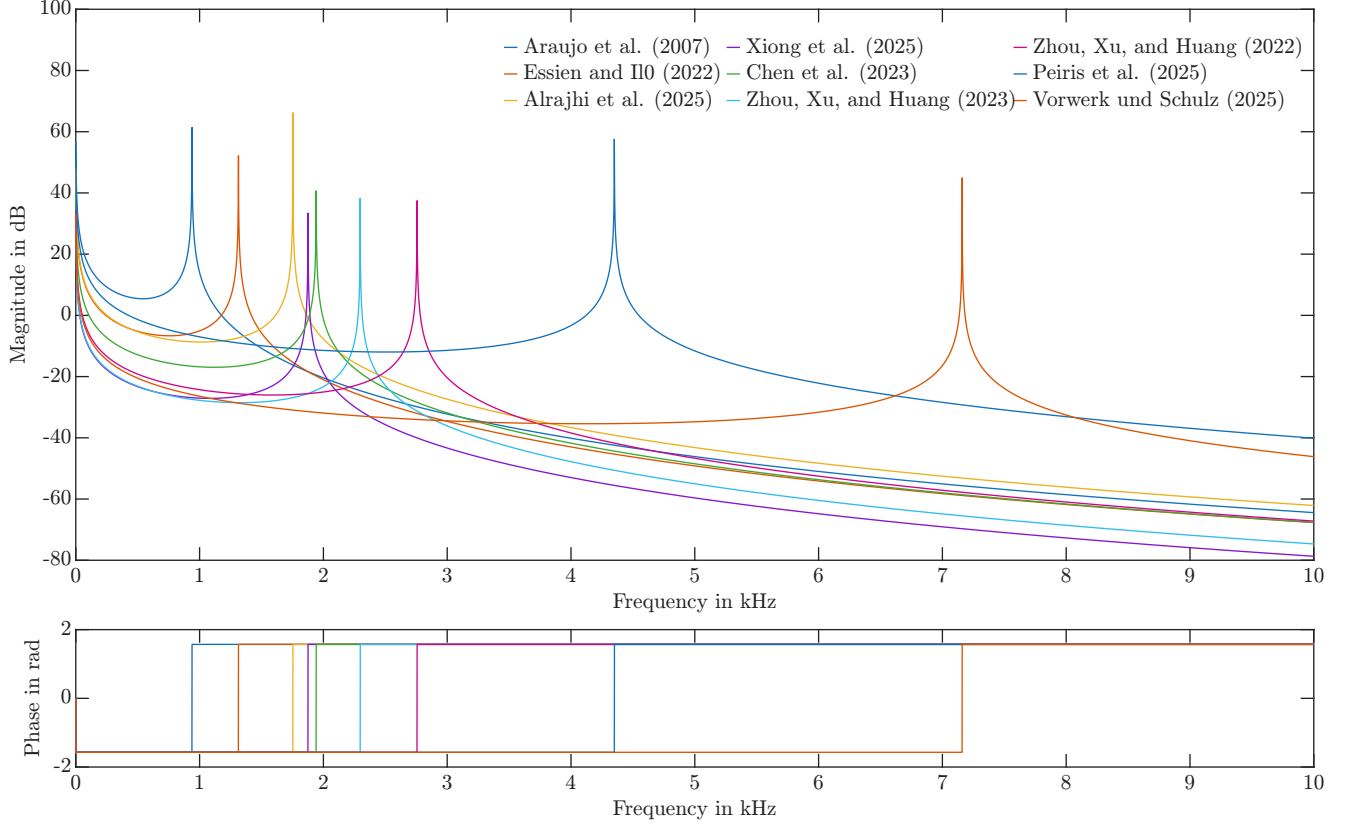


Figure 3.27: Typical LCL filter transfer functions with resonance peak. Filter parameters taken from Araujo et al. (2007) [104], Essien and Ilo (2022) [105], Alrajhi et al. (2025) [102], Xiong et al. (2025) [106], Chen et al. (2023) [107], Zhou et al. (2023) [103], Zhou et al. (2022) [108], Peiris et al. (2025) [109], and Vorwerk and Schulz (2025) [101].

According to Peiris et al. (2025) [109], Alrajhi et al. (2025) [102], and Zhou et al. (2023) [103], the LCL filter transfer function between the output current and the input voltage is:

$$\frac{i_{\text{out}}}{v_{\text{in}}} = \frac{1}{L_1 C (L_2 + L_g) \cdot (j\omega)^3 + (L_1 + L_2 + L_g) \cdot j\omega} \quad (3.1)$$

Figure 3.27 shows the Bode plot of this transfer function based on different LCL filter parameters reported in the literature. The selection is only an excerpt of the huge number of works dealing with optimizing LCL filter design. It aims at presenting the general variety of filter designs without claiming comprehensiveness. The additional grid-side impedance L_g is set to zero for comparability. All curves show the LCL filter response, with strong suppression towards high frequencies and a resonance peak at lower frequencies. Obviously, the resonance peak can lie at different frequencies, depending on the set filter parameters. The height of the resonance peak can be set by the damping resistor R_d , which is not considered here, so only the position of the peak along the frequency axis is discussed. A majority of resonance peaks lie around 1 kHz to 3 kHz. If an additional grid-side impedance L_g is included, the resonance peak shifts to lower frequencies (compare Equation 3.1 and [109]). In other words, the typical location of the resonance peak of LCL filters installed in inverters lies in the same frequency region where the alteration of the grid impedance due to the PV system is observed.

Overall, the presence of the PV alters the grid impedance magnitude around 1000 Hz. Due to the broadness of this frequency range that is influenced (as opposed to only an individual frequency), the alteration is likely caused by filter effects. The grid side filter of the inverter is the most prominent candidate. To further rule out the inverter control as the root cause, the next section investigates the dependence on PV injected power to the grid.

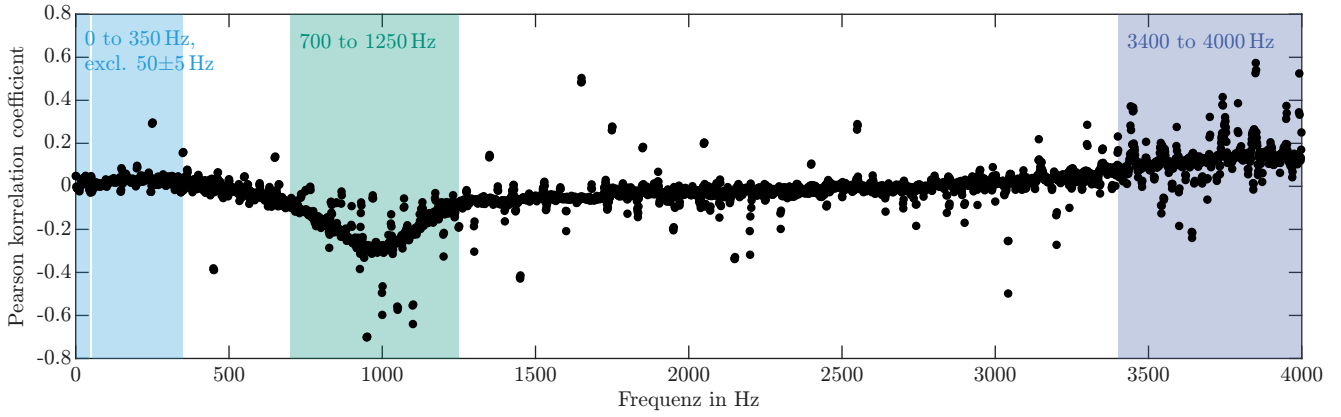


Figure 3.28: Correlation between voltage distortions and the inverter power, including times with disconnected PV system, show a strong negative correlation around 1000 Hz.

3.4.2 Additional Analysis: Effects are Independent from Inverter Power

Several studies report that the distortion behavior of inverters depends on their output power. For example, a recurrently reported fact is that the THD of the inverter current is higher at power outputs lower than the nominal power [19, 23, 24, 25, 26, 29, 30, 31, 32, 35, 110, 111, S3, S4, S5]. In contrast, the influence of different inverter power outputs on voltage waveform distortions remains unclear. As shown earlier (Chapter 1), the THD_V can be smaller or higher at low power output, or completely unaffected by the inverter power. The field measurements performed in this thesis and presented in Section 3.2 show that the rooftop PV system has a reductive influence on voltage waveform distortions in frequencies around 1000 Hz. This section investigates whether this reductive effect on voltage distortions is power-dependent. If the effect is indeed power-dependent, the inverter control most likely contributes to the change in voltage distortions.

The power dependence is investigated for each distortion component individually by calculating Pearson correlation coefficients between each distortion time series and the power time series. The Bravais-Pearson correlation coefficient estimates the strength and direction of a linear dependence between two variables. It was developed by Pearson (1895) [112] based on work by Bravais (1844) [113].

The forced shut-downs of the system in the course of the field measurement (see description and results in Subsection 3.2.1) took place over the course of two days with clear weather. As a result, they were induced at different power feed-ins of the PV system. Figure 3.11 in Subsection 3.2.1 shows the power time series during the field measurement, including artificial switching. The power time series is mainly characterized by the switching schedule and is zero whenever the PV system is disconnected. In addition, the typical day profile of a sunny day is visible in the power time series whenever the PV system is connected. Combined, the power data roughly follows a rectangular function with varying step size over the day. The figure also highlights the time ranges (purple for *PV off* and orange for *PV on*) that are included in the spectral analysis. One spectrum is available for each 1 s of voltage data during these times. Before correlation, the 15 s resolution power time series is linearly interpolated to match the 1 s resolution of the voltage distortion spectra. Then, each voltage spectrum $\mathcal{V}_k(t)$ (compare Subsection 2.4.1) can be assigned a respective power measurement.

Figure 3.28 shows the Pearson correlation coefficients between distortions and the power time-series. This includes the times when the PV system is disconnected, and the power is zero. Each distortion at a certain frequency is correlated individually with the same power time series, resulting in one coefficient per frequency. The correlation coefficients all lie in a distinct band. Only individual, mostly harmonic, frequencies deviate from the band towards much higher/lower coefficients. The band of coefficients is close to zero below 500 Hz and between 1500 Hz to 3500 Hz. Above 3500 Hz the coefficients increase towards positive values of up to 0.1 (band of majority of frequencies) or 0.6 (individual frequencies). Around 1000 Hz, negative (reductive) correlation is visible. Figure 3.28 also highlights the frequency ranges identified in Figure 3.13. At these frequencies, the PV system has a strong reductive (medium frequency region) or slightly increasing (high and low frequency

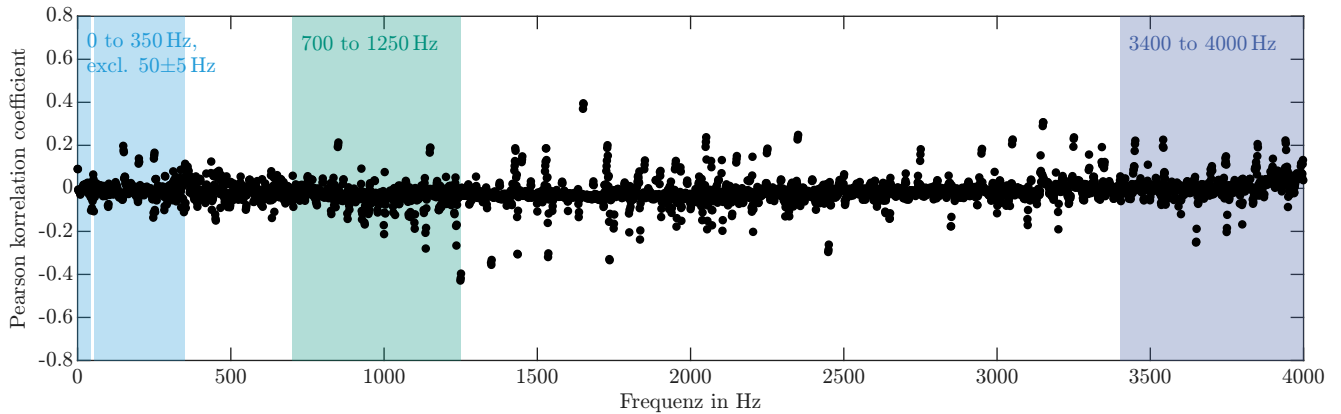


Figure 3.29: Correlation between voltage distortions and the inverter power, only during active PV system, show negligible correlation between distortions and PV power except for individual harmonic frequencies.

range) influence on grid voltage distortions. The moderate (≈ -0.4) negative correlation is observed in the same frequency region as the strong reduction of voltage distortions due to the connected PV system.

However, as the switching is included in the power time-series, the large absolute correlation coefficients do not necessarily show a correlation with power. Instead, the characteristic rectangular switching schedule might cause the non-zero coefficients. Section A.6 shows several scatter plots between individual distortions and the inverter power to help interpret the correlation coefficients. Especially the frequencies with large absolute coefficients in Figure 3.28 are selected. The scatter plots show that the identified correlation results from the shift of the distortion amplitudes from the state *PV off* (zero power) to *PV on* (different power values).

To focus the analysis on the power dependence only, Figure 3.29 shows the Pearson correlation coefficients between the voltage distortion amplitudes and the inverter power only for times when the PV system is running. These are the time ranges highlighted in orange in Figure 3.11. Times during which the system is powered down are excluded. Similar to Figure 3.28, the coefficients mainly lie in a distinct band. Only individual, mostly harmonic, frequencies lie outside of the band at larger/lower coefficients. However, in contrast to the correlation with the full power time series, here the majority of the coefficients lie close to zero. No correlation between the distortions and the inverter power during the active PV system is detectable. In addition, no change in the behavior of the coefficients in the different frequency regions is visible.

The influence of the PV system on voltage waveform distortions appears to correlate only with the connection state (*PV on/PV off*), not with the power injected by the system. A similar investigation, but on data acquired during normal operation of the system without artificial switching, is presented in [S1]. The same increased correlation of frequencies around 1000 Hz with the PV power is identified there and is attributed to the day/night switching of the inverters [S1]. Overall, the reductive effect of the PV on voltage waveform distortions in the medium-frequency range is found to be independent of the inverter power output. In contrast, effects related to the internal inverter control mechanisms are power-dependent.

3.4.3 Additional Analysis: Harmonic Inverter Currents Have Phase Angles that Increase Voltage Distortions

Voltage distortions in the public power grid are mainly caused by nonlinear loads. These types of loads draw non-sinusoidal currents and, as a consequence, cause a non-sinusoidal voltage response. How much the non-sinusoidal current draw influences the voltage depends on the grid impedance (Ohm's law). Similarly, the grid voltage waveform distortions are influenced by the connected PV system. Two different effects can be separated: First, there is a linear current response by the PV system's impedance characteristic. Second, the active current feed-in by the system. This subsection investigates whether the second effect, active current feed-ins by the PV system, is responsible for the frequency-dependent influence of the system on voltage

waveform distortions. Active current feed-in can be attributed to the underlying inverter control in contrast to currents originating from the output filters' response to the grid voltage. To this end, the phase angles of grid voltage distortions are compared with inverter current phase angles.

Subsection 4.1.2 introduces a frequency-domain equivalent model of a grid-connected PV system. According to Equation 4.4 therein, the grid voltage phasor V_G at the connection point of the PV system can be calculated for each frequency individually as

$$V_G = \frac{1}{\frac{1}{Z_S} + \frac{1}{Z_C}} \left[\frac{V_S}{Z_S} - I_C \right], \quad (3.2)$$

with the grid being represented by a voltage source (Thevenin equivalent of ideal voltage source V_S and series impedance Z_S). The PV system is represented by an ideal current source I_C (C for converter) and a parallel impedance Z_C (Norton equivalent) to represent its impedance characteristic. The grid voltage depends on both the PV system's impedance Z_C as well as the active current feed-in I_C . In order to investigate the voltage magnitude $|V_G|$, the phasors X are separated into their respective magnitude $|X|$ and phase angles φ_X representation ($X = |X|e^{j\varphi_X}$). The time development $e^{j\omega t}$ is also added:

$$V_G = \frac{\frac{|V_S|}{|Z_S|} e^{j(\varphi_{V_S} - \varphi_{Z_S})} - |I_C| e^{j\varphi_{I_C}}}{\frac{1}{|Z_S|} e^{-j\varphi_{Z_S}} - \frac{1}{|Z_C|} e^{-j\varphi_{Z_C}}} e^{j\omega t} \quad (3.3)$$

The grid voltage magnitude $|V_G| = \sqrt{V_G^* V_G}$ of this phasor is

$$|V_G| = \sqrt{\frac{\frac{|V_S|^2}{|Z_S|^2} + |I_C|^2 - 2 \frac{|V_S||I_C|}{|Z_S|} \cos(\varphi_{V_S} - \varphi_{Z_S} - \varphi_{I_C})}{\frac{1}{|Z_S|^2} + \frac{1}{|Z_C|^2} + 2 \frac{1}{|Z_S||Z_C|} \cos(\varphi_{Z_C} - \varphi_{Z_S})}}. \quad (3.4)$$

This equation holds for each frequency ω . Several parameters influence the magnitude of a voltage component, including the phase angles of individual voltages and currents generated by the sources. To interpret the equation, assume the voltage source supplies a distortion with constant magnitude $|V_S|$ and phase angle φ_{V_S} . Simultaneously, a current distortion of magnitude $|I_C|$ with the same frequency is fed in by the current source. Whether or not this current has a reductive or increasing effect on the overall grid voltage distortion magnitude $|V_G|$ depends on the cosine term in blue. The overall voltage magnitude is larger if the blue term is negative and smaller if it is positive. This depends on the current phase angle φ_{I_C} relative to the voltage phase angle φ_{V_S} as well as the source impedance phase angle φ_{Z_S} . Overall, $\cos(\varphi_{V_S} - \varphi_{Z_S} - \varphi_{I_C})$ is negative if $\frac{\pi}{2} < \varphi_{V_S} - \varphi_{Z_S} - \varphi_{I_C} < \frac{3\pi}{2}$. The magnitude of the influence depends on the impedance and current magnitude. The equivalent model shows that the inverter current can both increase and decrease the grid voltage magnitude $|V_G|$. However, the model does not represent the system in its complexity entirely. For example, the underlying control in the real system that makes the current source dependent on the observed grid voltage characteristic is not included. The exact functional dependence of the grid voltage on the inverter current could be more complex.

The measurement device described in Section 2.1 records the inverter current and voltage. For the investigation in this section, the current time series is analyzed for its spectral content in the same way as voltage signals (compare Subsection 2.2.2). This includes the extraction of phase angles for each distortion. As mentioned in Section 2.1, the current measurements are less accurate compared to voltage estimates. In addition, as discussed in Subsection 2.3.2, the extraction of phase angles is not very accurate due to the picked-fence effect. As a result, the evaluation of phase angles and current amplitudes contains potentially large errors and should be handled with care.

Figure 3.30 shows the distortion amplitudes (upper plots) and phase angles (lower plots) of the grid voltage V_k and inverter current I_k . The underlying waveform data of phase a was measured on the 16th of December, 2024, at 12:33:38 pm UTC during the impedance measurements (compare Subsection 3.4.1). At 12:32:38 pm, the PV system was running. The voltage distortion amplitudes are shown in the upper plot in Figure 3.30a. They are depicted relative to the fundamental component $V_{50\text{ Hz}}$ and show the same characteristics as observed for the grid voltage on the 20th and 21st of September, 2024 (compare Figure 3.12): Voltage distortion amplitudes are largest at harmonic frequencies. Interharmonic voltage distortions have smaller amplitudes. Both harmonic and interharmonic amplitudes decrease with frequency. The lower plot in Figure 3.30a shows the

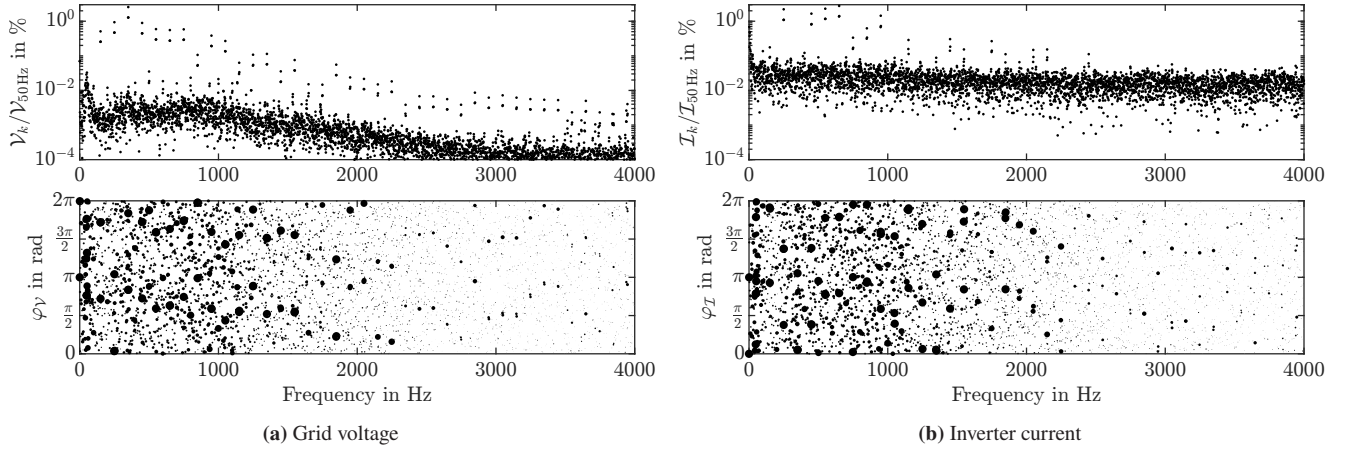


Figure 3.30: Amplitude and phase angle of grid voltage and inverter current distortions show a large variety of phase angles with no clear frequency-dependence.

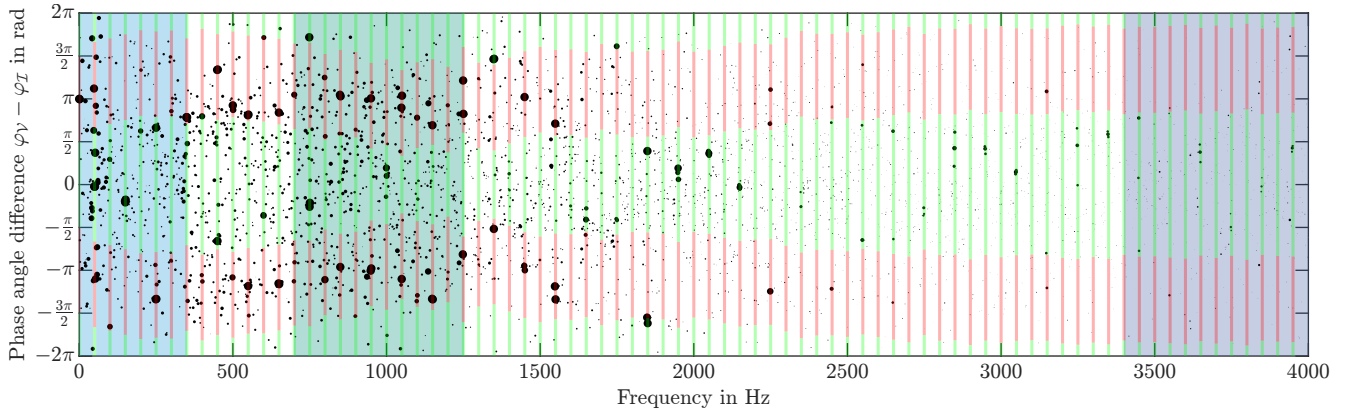


Figure 3.31: Phase angle difference between grid voltage and inverter current distortions does not show a different distribution around 1000 Hz compared to other frequencies.

phase angles φ_V of the voltage distortions. The size of phase-angle data points, as well as their grayscale, is proportional to the underlying distortion amplitude (shown in the upper plot): If the distortion amplitude is very small at a certain frequency, the data points are small and almost white. Components with large amplitudes are more visible. Because of the lower amplitudes at high frequencies, points become less pronounced towards the right. The distortion phase angles are distributed all over the range from 0 to 2π and change from one frequency to the next.

Figure 3.30b shows the current amplitudes I_k relative to the fundamental component $I_{50\text{ Hz}}$ in the upper plot. The inverter current also has high distortion amplitudes at harmonic frequencies. The fact that the inverter current copies grid voltage distortions at the same frequency is called auto-sensitivity and is a well-known dependence [13, 14, 16, 17, 18, 19, 20]. In addition to the harmonic content, the current shows interharmonic distortions at lower amplitudes. At low frequencies up to 1000 Hz, current distortions are in the same order of magnitude as the voltage interharmonics. However, the current interharmonics do not decrease with frequency and remain at the same level even for higher frequencies. The current distortion phase angles φ_I are shown in the lower plot in Figure 3.30b. Again, the size and grayscale of the data points are proportional to the voltage distortion amplitudes (not the current), to highlight frequencies with high voltage distortions. The current phase angles also span the entire range from 0 to 2π and do not change deterministically from one frequency to the next. Their values and behavior are hard to distinguish from those of the voltage phase angles. No clear interrelation between voltage and current phase angles is visible due to the variability from one frequency to the next.

To get a better view of the current phase angles relative to voltage phase angles, Figure 3.31 shows the difference $\varphi_V - \varphi_I$ between the two. Again, the data point size and grayscale are proportional to the underlying voltage distortion amplitude. In

addition, different frequency and phase angle regions are highlighted by a colored background. These will be discussed in more detail below. First, focusing on the black data points with high voltage distortion amplitude (large points), two different regions can be identified: At very low frequencies up to 150 Hz, the phase angle differences of components are close to zero or at least below $\frac{\pi}{2}$. At larger frequencies, between 150 Hz and 1200 Hz, the large and dark points group at two distinct levels, at roughly plus and minus π . At even higher frequencies, no grouping at any special value is visible. Towards the highest frequencies, the amplitudes are small, and thus the data points are vague and not discussed further here.

Figure 3.31 highlights regions of phase angle differences in red and green. The regions are identified based on Equation 3.4 and the impedance measurements described in Subsection 3.4.1. Explicitly, the phase angle φ_{Z_S} of the impedance measured in phase a on the 16th of December, 2024, at 12:29:22 pm is used. At this time, the PV system was still disconnected, and only the remaining grid impedance Z_S was measured. If the phase angle difference between voltage and current is in the red region, the overall grid voltage magnitude in Equation 3.4 is increased due to the current feed-in ($\cos(\varphi_{V_S} - \varphi_{Z_S} - \varphi_{I_C}) < 0$). In green regions, the inverter current would have a reductive effect on the grid voltage ($\cos(\varphi_{V_S} - \varphi_{Z_S} - \varphi_{I_C}) > 0$). Because impedance measurements are available every 50 Hz, only these harmonic frequencies are highlighted. In between these, no impedance phase angle measurements are available. At most frequencies, the harmonic data points (large black points due to high underlying voltage amplitude) lie in the red highlights. This means that these harmonic inverter current distortions have phase angles relative to the voltage distortion phase angles, which will cause an increase in voltage magnitude in Equation 3.4. Whether this transfers to the same behavior in the real system depends on the accuracy of both the underlying model representation and the phase angle extraction.

The three frequency ranges highlighted in Figure 3.31 (blue, turquoise, and purple) are the same as those identified in Figure 3.13. At these frequencies, the rooftop PV system has a slight increasing effect (low and high frequency range) or a strong reductive effect (medium frequency range around 1000 Hz) on grid voltage distortions. No special behavior of the phase angle differences is visible in the medium frequency region, compared to frequencies around 500 Hz, where no reduction of distortions was observed. In contrast to the reductive effect of the PV system on voltage waveform distortions in the medium frequency region shown in Figure 3.13, the harmonic frequencies in this region have phase angles that would cause an increase in voltage distortions (compare Figure 3.31). Figure 3.13 includes spectral averages over large time ranges (several hours in total) and the median of 80 separate shut-down events and shows broader percentile ranges around harmonic frequencies compared to interharmonic components. The fact that harmonic distortions potentially increase voltage distortions (compare Figure 3.31) can explain the high percentiles exactly at harmonic frequencies, because they behave differently compared to interharmonic components.

Overall, Equation 3.4 shows that active current feed-ins by the inverter can reduce or increase voltage waveform distortions. The phase angle of the current component relative to the phase angle of the voltage distortion at the same frequency and the impedance characteristic of the grid determine if the effect is reductive or increasing. The phase angles of voltage and current distortions relative to one another reveal no distinct behavior limited to the frequency region where the PV system reduces voltage distortions. Harmonic phase angles have values over a large range of frequencies that increase the grid voltage magnitude according to Equation 3.4. This argues against the active current feed-ins by the inverter control contributing to the reductive effect of the PV system on voltage distortions.

3.4.4 Summary and Discussion

Understanding the root cause of observed effects is essential for enabling their interpretation and for assessing their transferability to other systems and grid configurations. While the previous sections provided empirical evidence of frequency-dependent and installation-specific influences of PV systems on voltage waveform distortions, they did not yet explain the underlying physical mechanisms. To address this gap, the present section investigates the root cause of these effects using additional measurements and analyses conducted on the rooftop PV system. In particular, impedance measurements were performed to examine changes in the overall grid impedance when the PV system is connected. Further analysis of voltage, current, and power data allows assessment of potential dependencies on power levels and the role of inverter current injection. In

addition, instead of maintaining the full PV system view, the multitude of components included in the system (e.g., the PV panels or the inverter) are considered directly. The results show that the connection of the PV system leads to a measurable change in the overall grid impedance. Notably, this change occurs in the same frequency range in which a reduction in voltage waveform distortions was previously observed. This strongly indicates that the effect may be predominantly linked to the grid-side output filter of the inverter, which alters the overall grid impedance whenever connected. In contrast, no significant dependence of the distortion behavior on the system's power output could be identified. The frequency-dependent influence remains consistent across shutdown events at different times of day and power levels. Furthermore, the analysis of phase angles reveals no evidence that active current injection with a specific phase shift is responsible for the observed reduction in distortions. Instead, the measured harmonic current components tend to exhibit phase angles that would increase, rather than reduce, voltage distortions. Together, the absence of power dependence and the observed phase angle relations suggest that the active inverter control scheme is unlikely to be the primary cause of the effect.

The root-cause analysis benefits from multiple complementary investigative approaches, including impedance measurements, power correlation analysis, and phase angle evaluation. The impedance measurements are particularly insightful, as they directly link the observed changes in voltage distortions to modifications of the overall grid impedance caused by the PV system, strengthened by their consistency across multiple shutdown events. The power analysis leverages a wide range of operating points obtained during two consecutive sunny days and employs correlation-based methods to assess dependencies across the full spectral range. Additional analyses confirm that the detected correlations are primarily associated with switching events rather than with continuous variations in power output. The phase angle analysis, although limited to harmonic components due to methodological constraints, is supported by analytical considerations demonstrating that both increasing and decreasing effects on voltage distortions are theoretically possible depending on the phase relationship and the underlying impedance.

Despite these strengths, the results do not fully resolve all aspects of the observed behavior. While strong indications for the role of the inverter output filter are found, other contributing mechanisms cannot be entirely excluded. In particular, the influence of internal active control schemes, although not supported by the observed data, cannot be definitively ruled out due to limited access to system internals. Each analysis approach also introduces its own limitations: Impedance measurements are restricted to harmonic frequencies and were conducted on a single day, while correlation-based power analysis may be affected by underlying data distributions. Phase angle estimation is subject to measurement uncertainties and methodological inaccuracies, especially when derived from discrete spectral analysis. Further limitations arise from the incomplete characterization of the system and its environment. The PV system has to be treated as a black box, and detailed information about its internal filter design is not available. This restricts the depth of interpretation and prevents direct modeling of the observed behavior. Moreover, impedance measurements capture only the combined response of the grid and the connected system, making it difficult to isolate the contribution of the PV system alone.

These findings have important implications. They demonstrate that the influence of PV systems on voltage waveform distortions is strongly influenced by the interaction between the inverter's output filter and the connected grid's impedance. As both of these factors vary significantly between installations, the resulting behavior is inherently system-specific and difficult to predict. In addition, PV installations are just one example of IBR, and the same behavior is expected for all systems that include an inverter-based connection to the grid. The results also highlight that, in the absence of detailed system knowledge, impedance- and measurement-based approaches provide a valuable first step towards understanding such effects. Future work could aim to deepen the investigation of the identified mechanisms. One promising direction is the isolated analysis of inverter output filters, decoupled from the influence of control systems. An intrusive option to do this is to separate the filter from the switching hardware of the inverter to analyze its isolated impedance characteristics. However, this approach is not suitable for widespread field application as it may at least void warranty claims and at most permanently damage the system. A more feasible approach would be a dedicated operating mode of the inverter where the grid-side filter is connected, but no power feed-in or control is active. Finally, as outlined in the following section, extending the analysis to additional PV systems and grid configurations will help to quantify the variability of these effects.

In conclusion, the inverter's grid-side output filter is identified as the primary contributor to the observed frequency-dependent effects. Given the variability of both filter characteristics and grid conditions, it follows that the influence of PV systems will differ between installations, as was observed in the previous section. This underscores the necessity of system-specific analysis and further motivates the continued investigation of these effects across a broader range of real-world configurations.

3.5 Contributions and Future Work

A new field measurement method was presented in Chapter 2 that assesses the influence of PV systems on voltage waveform distortions. Both a measurement approach using repeated induced disconnection of the system and a non-intrusive option for systems that do not allow forced switching are available. In this chapter, three different PV systems were characterized using the new method: A rooftop system, a PV field, and a system installed in an energy-system research lab. They are real-world, commercial systems that cover a large variety of potential installations.

The rooftop PV system reduces grid voltage distortions between 700 and 1250 Hz by up to 40 %. Simultaneously, it increases distortions at frequencies below 350 Hz and above 3400 Hz, but the increase is less pronounced compared to the distortion reduction. Both variations of the developed field-measurement method are applied to the system, and they all show the reduction of voltage distortions around 1000 Hz. Another system, the PV field, shows a different influence on voltage distortions: distortions between 300 Hz to 800 Hz and above 2250 Hz are increased, and distortions between 800 Hz to 2200 Hz are reduced by the PV field. As no induced switching options were possible for the PV field, the non-intrusive approach had to be used on the system, proving the importance of the option for the restrictive real-world investigations. A third system (SYSLAB system) connected to the public grid increases distortions above 2000 Hz; lower frequencies are unaffected by the system (zero change in distortions due to disconnection of the system). In contrast, when operating the system in an isolated grid, powered by a grid emulator, the PV system alternately increases distortions (600 Hz to 1100 Hz, 1400 Hz to 2100 Hz, 3000 Hz to 3300 Hz) and decreases distortions (around 1250 Hz and 2700 Hz), depending on the frequency. In both grid settings, the robust approach with induced switching was applied to the SYSLAB system to characterize the distortion changes.

All investigated systems agree on the following aspect: The influence of the PV installation on the voltage waveform depends on the frequency of the distortion (spectral component in the frequency domain). In addition, each system shows an individual distortion characteristic. The connected grid characteristic also contributes to the behavior: A PV system investigated in one grid can have a different effect on voltage waveform distortions in another grid with different generator and load composition. Overall, the influence of PV systems on voltage waveform distortions is frequency-sensitive, installation-specific, and depends both on the specific system and the currently connected grid. Any future investigation on PV systems in the context of voltage waveform distortions needs to take this into account, maintain a spectral perspective, and evaluate the PV and connected grid as a joint system. The new characterization method presented in this thesis provides the necessary high spectral resolution, is straightforward to apply in the field, and clearly attributes changes in voltage distortion to the system under investigation.

In addition to the system characterizations, the rooftop PV system was analyzed in more detail to deduce the root cause of the observed effect. Additional impedance measurements reveal that the system changes the overall grid impedance in the same frequency region where it reduces distortions. Also, the changes in voltage waveform distortions due to the rooftop PV system are independent of power. Explicitly, the reductive effect on voltage waveform distortions is the same for all shutdowns over the day that occur at different operating points. An analysis of harmonic voltage and current distortion phase angles reveals that the relation between the two cannot explain the reduction of distortions. This means the implemented control scheme of the inverter is likely not the cause of the observed distortion reduction. Instead, the impedance measurement, power dependence, and phase angle analysis attribute the effect mainly to the grid-side hardware filter of the inverter. The PV system adds a frequency-dependent impedance that contributes to the overall grid impedance and thus influences the present voltage waveform distortions. The filter characteristic and the underlying grid impedance can change for each system and grid connection point. As a result, the changes in voltage distortions will look different in every system, as was observed in the field measurements.

The characterizations of each system acquired in this thesis are consistent and, thus, longer data acquisitions were not pursued. Nonetheless, an extension of the data acquisition and analysis of the systems already investigated is always possible by measuring for more days, in different seasons, or at different inverters of the same system. However, a much more significant next step is to characterize even more PV systems. This will allow a better overview of how strong the influence can be and what percentage of installations are dominant enough relative to the grid to have a meaningful influence on voltage distortions. To know exactly what parts of the observed behavior are directly caused by the inverter's grid-side filter, this thesis also proposes one additional measurement: Investigate the inverter in an operational state in which the grid filter is connected, but no power is fed in (called standby, grid observation, ...). To force the inverter into such a state, sufficient access rights to the system are required. Explicitly, the password to the device control and settings interface, which is usually only known to installers, is necessary. The next step would then be to compare the voltage distortions for three different states: In normal operation with power feed-in, completely shut down with disconnected filter, and the intermediate state with filter connected but reduced control activity. However, such an approach is only applicable if the inverter itself allows such an operating mode.

Nonetheless, this thesis proves that PV systems can, indeed, have a reductive effect on voltage distortions. Also, in extension, the same potential holds for all other IBR besides PV systems, with the inverter identified as the root cause of the behavior. This insight holds the opportunity to extend grid-supporting services provided by inverters towards distortion management: The individual impedance characteristic of a system would be adapted to the connected grid's requirements. For example, to specifically reduce distortions in frequency regions where they often occur in the grid in question. In any case, frequency-sensitivity and system-specific behavior of PV systems have to be taken into account when investigating distortions in larger-scale grid studies. To this end, the following chapter transfers the insights presented here to the simulation domain. A modeling approach, including parametrization based on measurements, is presented that incorporates the frequency-dependent change in voltage waveform distortions.

4 Model Representation

The previous chapter characterized three different PV systems directly in the field towards their influence on voltage waveform distortions. It was found that the changes in voltage distortions are frequency sensitive. For example, the rooftop PV system reduces voltage distortions around 1000 Hz while increasing them in low- and high-frequency regions. In addition, each system has its own individual characteristic; the voltage distortion changes are system-specific. Finally, the same system connected to two different grid compositions has two distinct characteristics; the connected grid influences how distortions are influenced by the PV system. This chapter presents a modeling approach that can capture this frequency-dependent effect of the PV system on voltage waveform distortions. The model will also be presented in a publication currently being drafted together with the measurements presented in Section 3.3. First, Section 4.1 starts with a literature review of the multitude of different modeling approaches and research questions addressed in the context of PV systems. It also identifies the requirements for the modeling approach to be developed here and selects the best modeling approach based on reported models. In addition, the selected approach is evaluated analytically to prove its theoretical capability of incorporating the measured characteristics. The model is implemented in DIgSILENT PowerFactory (see Section 4.2). This includes the parametrization of the model based on measured data. Explicitly, a new measurement approach is presented that allows extracting the frequency-dependent impedance of a grid-following PV system, which does not allow isolated measurements without the grid.

4.1 Modeling Approach: Frequency Domain Equivalent Circuits as Best Option

The present section lays the theoretical basics for the overall goal of this chapter: A representation of the found frequency-dependent change in voltage waveform distortions due to PV systems in simulation. With a broad literature review of simulation studies in the context of PV systems, studies with a special focus on voltage distortion are identified (see Subsection 4.1.1). Requirements for the model in the present application are also identified and used to select a suitable modeling approach among the multitude of available options. Subsection 4.1.2 then presents fundamental equations that analytically prove the capability of the selected modeling approach to incorporate frequency-dependent voltage distortion changes due to a connected PV system.

4.1.1 Literature Review: Frequency Domain Models are Computationally Efficient

Models of PV systems are used for various applications like prediction of generated power based on weather data [114, 115, 116, 117], increasing system efficiency [118, 119], design of model predictive control [120, 121, 122, 123, 124, 125, 126, 127], or ensuring system stability [128, 129, 130, 131, 132, 133, 134, 135, 136, 137]. Even reduced to the special field of power quality, a multitude of different research focuses remain. These include general power quality investigations [138, 139, 140, 141], the analysis of resonances [141, 142] and oscillations [86, 107, 135, 143, 144, 145, 146, 147, 148, 149], harmonic emissions and mitigation [68, 103, 105, 146, 150, 151, 152, 153, 154, 155], and high-frequency emissions [156, 157]. Each of the aforementioned applications uses specialized models optimized for the individual research goal or investigated effect. This is necessary because a tradeoff exists between the model detail necessary to correctly reproduce an effect and the available computational resources to run the simulation. It is known that simple models often do not correctly predict the behavior of the

modeled system [60, 61, 62, 63, 64]. Excessively complex models, in contrast, are impractical as they require too much time for processing or expensive computational facilities. Instead, model type and complexity are adapted to a specific application.

Designing and implementing a new model is complex and often not feasible [S3]. Thus, many platforms provide exemplary system models that are easy to use [158, 159]. However, these are not necessarily capable of reproducing all behaviors of a real system and need to be optimized towards a specific application or system before use. For example, MATLAB/Simulink models of PV systems are available but have to be modified to correctly incorporate the power-dependent and auto-sensitive inverter current waveform [S3]. For such an optimization of a given model towards a certain application, effect, or system, it is necessary to have additional information, like the internal circuit or control setup of a device. This thesis focuses on characterizing commercial PV systems in-field. Unfortunately, in the case of such commercial systems, not much information is available due to proprietary restrictions by the manufacturers [60, 62, 63, 64, 119, 160, 161]. If, as in the present case, detailed information and documentation on the system are not available, other information sources can be used to derive an appropriate model: The simulation results can be compared with those of more detailed models [146, 162, 163, 164, 165, 166, 167, 168, 169, 170], laboratory measurements [89, 135, 146, 147, 150, 165, 166, 167, 169, 171, 172, 173, 174, 175, 176, 177], or characterizations of the system in-field [92, 178, 179].

This thesis focuses on voltage waveform analysis on a broad and detailed spectral level. In other words, many different spectral components are analyzed simultaneously. The goal of this chapter is to represent the influence of PV systems on voltage waveforms in simulation. This is necessary to correctly incorporate the effects in larger grid studies. It was found that each PV installation can cause a different change in voltage distortions. Thus, every system requires its own specialized model representation. This results in three requirements that have to be met by the final model: First, the model must be capable of correctly predicting voltage distortions at different frequencies. Second, it must be computationally effective to be applicable as part of a large grid simulation, which is limited by computational resources. Third, it must be fast and easy to create and calibrate to allow adaptation to all the different systems present in the grid. A multitude of different modeling options exist that can simulate waveform distortions. They can be categorized into different types:

- Models are characterized by being either black-box, gray-box, or white-box models [180]. The latter includes models with full knowledge of the internal components of a system; for example, circuit and control behavior are modeled in detail. In contrast, if such detailed information is not available, as in the present case, black-box models are used. They use a system representation using aggregated or effective parameters and functions instead of a detailed internal system representation. Gray-box models lie in between these two extremes; for example, they only model some parts of the system in detail.
- Models are either a small-signal or a large-signal representation: The former are models that use linearization to approximate the behavior of the system around a specific operating point. This reduces complexity but limits the applicability of the model to a narrow parameter space around the point of linearization. In contrast, large signal models cover a larger range of operating points and are capable of reproducing transient behavior. Examples for the latter are the Hammerstein-Wiener (HW) (HW) model [176, 180, 181], as well as models based on Artificial Neural Network (ANN) [60, 61, 152, 168, 180, 182, 183]. However, the HW model requires an extensive iterative calibration process to accurately capture a system's behavior, and the ANN must be trained with a large and high-quality training dataset. The advantage of the wider parameter space available with large-signal models comes at the cost of time-consuming model creation. Thus, they are not feasible for fast characterization of many individual systems.
- When investigating waveform distortions, models are designed either in the time or frequency domain. In the time domain, the behavior (for example, the current and voltage output) of the system is calculated for consecutive points in time. To include effects at higher frequencies, for example, the internal switching of an inverter, the time resolution of the computation has to be high. Explicitly, twice as high as the maximum frequency of interest (as required by the Nyquist criterion). These so-called Electro-Magnetic Transient (EMT) models require large computational resources for the required high number of data points in the time domain. In addition, the model requires detailed knowledge about the modeled system to correctly incorporate all transient effects and non-idealities (e.g., of switches), which are visible in high time resolutions. In contrast, less complex time-domain RMS models are restricted to effects at smaller

frequencies due to the underlying averaging that filters out high frequencies [149, S6]. In contrast, frequency-domain models are the most computationally effective for investigating a high number of spectral components simultaneously. They calculate the behavior of the system at different frequencies individually instead of computing the high-resolution time-domain waveform and can be parametrized based on measured frequency characteristics of the system.

Overall, small-signal, frequency-domain, black-box models are well-suited to capture the frequency-dependent behavior of the system while allowing fast characterization and requiring less computational resources compared to more complex and detailed modeling approaches. Prominent examples are impedance- [91, 92, 128, 183, 184, 185, 186] and admittance-based models [95, 128, 173, 187]. In circuit representation, these models consider the grid and connected system as so-called Norton and Thevenin equivalents [147, 175, 185, 188]. These will be discussed in more detail in the following section that analytically derives how the equivalents can represent the observed frequency dependence.

4.1.2 Analytical Approach: Changes in Voltage Components Due to Changed Impedance Characteristic

The field measurement results presented in Section 3.2 showed that the rooftop PV system reduces grid voltage waveform distortions at certain frequencies while increasing them at other frequencies. This section lays the analytical foundations to capture these experimental observations in a model. According to the previous section, small-signal, frequency-domain models are the best-suited modeling approach for this application.

The following calculations are based on representing the alternating voltages and currents $x(t)$ using phasors: $x(t) = X e^{j\omega t}$. Upper case letters X refer to the phasor representation of a quantity: $X = \hat{x} e^{j\varphi_x}$. They include the phase angle φ_x and amplitude $\hat{x}$ of the quantity. The latter equals the magnitude $|X| = \hat{x}$ of the phasor. ω is the rotational frequency of the sinusoidal variable. X can either stand for the complex voltage phasor V or the complex current phasor I . The impedance $Z = R + jX$ is also complex, with the resistance R as the real part and the reactance X as the imaginary part. In the frequency-domain representation of the system, all three quantities ($V(\omega)$, $I(\omega)$, and $Z(\omega)$) are defined separately for each considered frequency ω .

The small-signal behavior of a system around a certain frequency can be represented by Norton and Thevenin equivalent circuits [188]. A representation of the combined system of grid and connected PV system is shown in Figure 4.1. Figure 4.1a shows the grid equivalent of an ideal voltage source V_S and a series impedance Z_S on the left-hand side (Thevenin equivalent). The PV system on the right-hand side is represented by a current source I_C (C for converter) and a parallel impedance Z_C (Norton equivalent). All non-idealities of the current and voltage source are encoded in the connected impedances. An impedance Z_L representing other loads in the grid is also included. The grid voltage V_G is measured at the connection point of the PV system to the grid, same as in the field measurement. For simplification, the two parallel impedances Z_L and Z_C are combined to one impedance Z_P through which the current I_P flows (see Figure 4.1b).

According to Ohm's law, the voltage drop V_Z across an impedance Z equals the current I_Z flowing through it, multiplied by the impedance: $V_Z = Z \cdot I_Z$. For the circuit diagram in Figure 4.1b, this gives the following equations

$$V_{Z_P} = Z_P \cdot (-I_P), \quad V_{Z_S} = Z_S \cdot I_S \quad (4.1)$$

Kirchhoff's current/junction law states that the sum over all currents flowing into a junction equals the sum of currents flowing out of the junction: $\sum I_k = 0$. Applied to the circuit diagram in Figure 4.1b this gives

$$I_P = I_S + I_C. \quad (4.2)$$

Similarly, Kirchhoff's voltage/loop law is $\sum U_k = 0$: The sum over voltages in a loop is zero. For the left-hand loop in Figure 4.1b this gives

$$V_G = V_{Z_P} = V_S + V_{Z_S}. \quad (4.3)$$

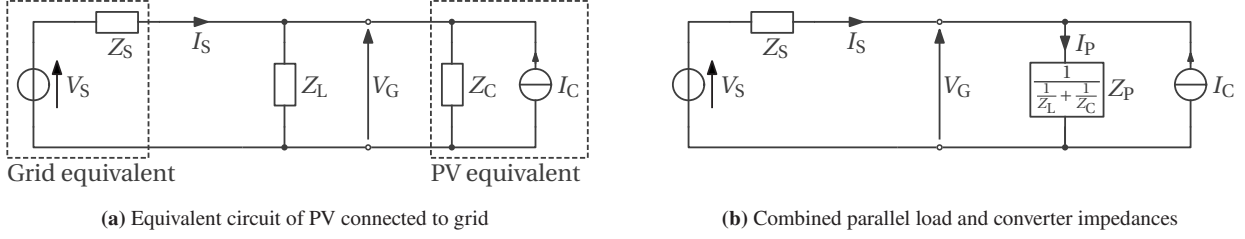


Figure 4.1: Equivalent circuit diagram of the PV system connected to the grid using Norton and Thevenin equivalents.

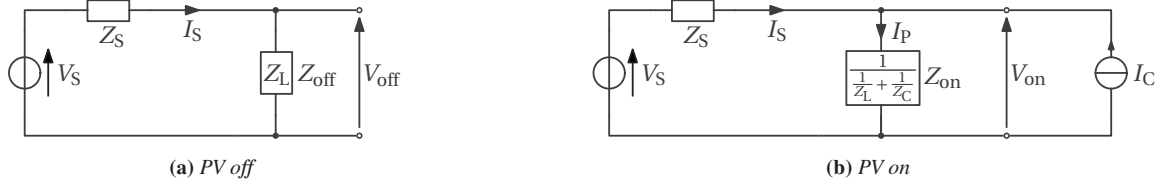


Figure 4.2: Equivalent circuit diagram with and without the PV system connected to the grid allows to calculate the effective grid voltage $V_{on/off}$ in both cases.

Based on these equations, the grid voltage can be expressed using only known quantities (V_S , I_C , as well as the impedances Z_S and Z_P):

$$\begin{aligned}
 V_G &\stackrel{(4.3)}{=} V_S + V_{Z_S} \stackrel{(4.1)}{=} V_S + I_S \cdot Z_S, \\
 &\stackrel{(4.2)}{=} V_S + Z_S(I_P - I_C) \stackrel{(4.1)}{=} V_S + Z_S \left(\frac{-V_{Z_P}}{Z_P} - I_C \right), \\
 &\stackrel{(4.3)}{=} V_S + Z_S \left(\frac{-V_G}{Z_P} - I_C \right), \\
 \Leftrightarrow V_G \left(1 + \frac{Z_S}{Z_P} \right) &= V_S - Z_S I_C, \\
 \Leftrightarrow V_G &= \frac{V_S - Z_S I_C}{1 + \frac{Z_S}{Z_P}} = \frac{1}{1 + \frac{Z_S}{Z_P}} V_S - \frac{Z_S}{1 + \frac{Z_S}{Z_P}} I_C, \\
 &= \frac{1}{\frac{1}{Z_S} + \frac{1}{Z_P}} \frac{V_S}{Z_S} - \frac{1}{\frac{1}{Z_S} + \frac{1}{Z_P}} I_C = \frac{1}{\frac{1}{Z_S} + \frac{1}{Z_P}} \left[\frac{V_S}{Z_S} - I_C \right]. \tag{4.4}
 \end{aligned}$$

The grid voltage phasor at a certain frequency depends on both the grid equivalent voltage and series impedance, as well as the inverter current. It is scaled by the series and parallel impedances.

Similar to the field measurement, the circuit in Figure 4.1 can be analyzed with and without the PV connected. This is visualized in Figure 4.2. For just the Thevenin grid equivalent in Figure 4.2a Kirchhoff's voltage law gives $V_{off} = V_{Z_{off}} = V_S + V_{Z_S}$. And, according to Ohm's law, the voltage drop over Z_S is $V_{Z_S} = Z_S \cdot I_S$ and over Z_{off} it is $V_{Z_{off}} = Z_{off} \cdot (-I_S)$. Together, these result in

$$V_{off} = V_S + Z_S \cdot I_S \quad \Leftrightarrow \quad I_S = \frac{V_{off} - V_S}{Z_S} \tag{4.5}$$

$$V_{off} = V_{Z_{off}} = Z_{off} \cdot (-I_S) \stackrel{(4.5)}{=} \frac{Z_{off}}{Z_S} (V_S - V_{off}) \quad \Leftrightarrow \quad V_{off} = \frac{Z_{off}}{Z_{off} + Z_S} V_S \tag{4.6}$$

According to Equation 4.4 the grid voltage V_{on} in Figure 4.2b with the system connected is

$$V_{on} = \frac{1}{\frac{1}{Z_S} + \frac{1}{Z_{on}}} \left[\frac{V_S}{Z_S} - I_C \right] \tag{4.7}$$

The relative difference defined in Equation 2.13 between the different voltages (same equation as used on measured data) in these equivalent circuits is

$$\begin{aligned}
 \Delta_{\text{rel}} V &= 2 \cdot \frac{V_{\text{on}} - V_{\text{off}}}{V_{\text{on}} + V_{\text{off}}} \\
 &= 2 \cdot \frac{\frac{1}{\frac{1}{Z_S} + \frac{1}{Z_{\text{on}}}} \left[\frac{V_S}{Z_S} - I_C \right] - \frac{Z_{\text{off}}}{Z_{\text{off}} + Z_S} V_S}{\frac{1}{\frac{1}{Z_S} + \frac{1}{Z_{\text{on}}}} \left[\frac{V_S}{Z_S} - I_C \right] + \frac{Z_{\text{off}}}{Z_{\text{off}} + Z_S} V_S} \cdot \frac{\left(\frac{1}{Z_S} + \frac{1}{Z_{\text{on}}} \right) (Z_{\text{off}} + Z_S)}{\left(\frac{1}{Z_S} + \frac{1}{Z_{\text{on}}} \right) (Z_{\text{off}} + Z_S)} \\
 &= 2 \cdot \frac{(Z_{\text{off}} + Z_S) \left[\frac{V_S}{Z_S} - I_C \right] - \left(\frac{1}{Z_S} - \frac{1}{Z_{\text{on}}} \right) Z_{\text{off}} V_S}{(Z_{\text{off}} + Z_S) \left[\frac{V_S}{Z_S} - I_C \right] + \left(\frac{1}{Z_S} - \frac{1}{Z_{\text{on}}} \right) Z_{\text{off}} V_S} \\
 &= 2 \cdot \frac{\left[1 - \frac{Z_{\text{off}}}{Z_{\text{on}}} \right] V_S - [Z_{\text{off}} + Z_S] I_C}{\left[1 + 2 \frac{Z_{\text{off}}}{Z_S} + \frac{Z_{\text{off}}}{Z_{\text{on}}} \right] V_S - [Z_{\text{off}} + Z_S] I_C} \quad (4.8)
 \end{aligned}$$

The term $[Z_{\text{off}} + Z_S] I_C$ is the same in both numerator and denominator. A change in the voltage phasor at a given frequency due to the presence of the PV system in the grid is caused by either the voltage and current injections by the sources (V_S and I_C), the present impedances that react to the voltages and currents, or the relative size of the quantities. For example, the impedance ratio $\frac{Z_{\text{off}}}{Z_{\text{on}}}$ plays a central role in determining the change in voltage amplitude at a given frequency.

To use the model in Figure 4.1 as an equivalent for a real-world system, the values for impedances, current, and voltage source have to be set at each frequency individually. Such a model parametrization is derived in the following section for an implementation in PowerFactory. It can then be used to investigate how the voltage amplitude changes, depending on the underlying impedance at a certain frequency.

4.1.3 Summary and Discussion

A variety of modeling approaches exist for analyzing the influence of distributed energy resources on power systems, each tailored to a specific application and level of detail. In this work, an equivalent frequency-domain model has been identified as the most suitable approach for the considered application. Within this framework, analytical investigations demonstrate that variations in voltage distortion amplitudes at different frequencies depend on two influences: The relative impedance of the system with and without the PV system connected and the injected PV current. This highlights the impedance as a central quantity for assessing the PV system's influence on voltage distortions.

The selected modeling approach offers several important advantages: It accommodates the black-box nature of the investigated system, avoiding the need for detailed knowledge of internal circuit and control algorithms. At the same time, it remains computationally efficient and allows a high frequency resolution, making it well-suited for the analysis of frequency-dependent phenomena. Furthermore, the model provides a foundation for subsequent investigations, such as stability analysis in the frequency domain. Any model-based representation is simplified compared to the real-world system. For example, the real systems may involve additional impedances or different interconnections that are not captured. Moreover, the complex and interdependent control algorithms of the PV system are not explicitly represented. The model is therefore restricted to analyzing the specific mechanism under consideration.

In conclusion, impedance-related effects of PV systems on voltage distortions can be captured using frequency-domain equivalent models, making them a valuable tool for analysis and further investigations. Future work could focus on extending the model to incorporate additional system complexity, including more detailed representations of network impedances and control dynamics. Such enhancements would improve the model's applicability and accuracy for a broader range of scenarios. But first, the following section further validates the selected modeling approach as-is by adapting the model to a specific system and comparing the simulated results with the field measurement performed on that same system.

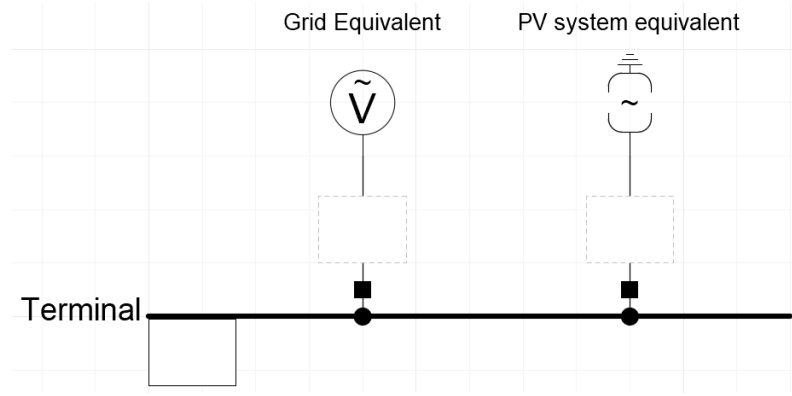


Figure 4.3: Schematic DigSilent PowerFactory model with voltage and current source representing a grid-connected PV system.

4.2 Results: Calibrated Model Correctly Predicts Changes in Voltage Components

The previous section identified a suitable modeling approach to represent the frequency-dependent changes in voltage distortions due to connected PV systems. This frequency-domain impedance-based model is computationally efficient and only requires equivalent parametrization instead of detailed information on the internal setup and control algorithms of the systems. In the following, this model is implemented in PowerFactory (see Subsection 4.2.1). To do this, Subsection 4.2.2 develops a new parametrization approach to extract the frequency-dependent impedance of the grid-following PV system without being able to measure it isolated from the grid. With this parametrization, Subsection 4.2.3 proves that the specialized model is capable of capturing the same changes in voltage distortions due to the rooftop PV system that were observed in the field measurement.

4.2.1 Fundamentals: Frequency Domain Models in PowerFactory

DigSILENT PowerFactory is a simulation tool for electrical power grid studies [189]. It is well-suited and often used for large-scale grid studies, including a high number of components. Within its *Power Quality and Harmonic Analysis* calculation framework, it allows the simulation of systems in the frequency domain [190]. The circuit in Figure 4.1 representing a grid-connected PV system is here implemented as the Power Factory Model in Figure 4.3 (version 2025, service pack 3). The public grid to which the PV system is connected is represented by a real voltage source (ideal source with series impedance defined by the resistance R and the reactance X). The connected PV system equivalent is a real current source (ideal current source and a parallel admittance Y with conductance G and susceptance B). The admittance is the inverse of the impedance $Y = \frac{1}{Z} = \frac{R}{R^2 + X^2} - j \frac{X}{R^2 + X^2} = G + jB$.

The *Power Quality and Harmonic Analysis* is the frequency-domain modeling approach in PowerFactory. It allows two different simulation modes: Frequency Sweep and Harmonic Load Flow [190]. The former calculates the network impedance of the model for a set of pre-defined frequencies. The latter performs a load flow for each frequency at which a source is present in the system, resulting in a spectrum of calculated values at each frequency. For example, a voltage amplitude spectrum. This allows observing frequency-dependent effects. For these frequency-domain calculations, all parameters in the model also have to be defined at different frequencies: Voltage and current sources generate output at different frequencies in addition to the fundamental 50 Hz component, and frequency-dependent impedance characteristics are set for all components.

In PowerFactory, all parameters are defined in symmetrical components. For that reason, a few fundamental definitions are introduced in the following. A phase quantity $\mathbf{X}_p = [X_a, X_b, X_c]$ (e.g., a voltage or a current) is transformed to symmetrical components $\mathbf{X}_s$ by a linear transformation introduced by [191]. Matrices and vectors are depicted in bold:

$$\mathbf{X}_s = \begin{bmatrix} X_0 \\ X_1 \\ X_2 \end{bmatrix} = \mathbf{S}\mathbf{X}_p = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \quad (4.9)$$

with $\alpha = \exp\left(\frac{2\pi}{3}j\right) = \sqrt[3]{1}$ and $s = 0$ for zero, $s = 1$ for positive, and $s = 2$ for negative sequence.

In agreement with [192], the impedance in symmetrical components, the sequence impedances $\mathbf{Z}_s$, is given by

$$\mathbf{Z}_s = \mathbf{S}\mathbf{Z}_p\mathbf{S}^{-1} \quad (4.10)$$

If the system is balanced and uncoupled, the phase domain impedance is represented by the following matrix

$$\mathbf{Z}_{,p} = \begin{bmatrix} Z & 0 & 0 \\ 0 & Z & 0 \\ 0 & 0 & Z \end{bmatrix}, \quad (4.11)$$

and it holds [192]

$$\mathbf{Z}_S = \mathbf{Z}_P. \quad (4.12)$$

In a balanced and uncoupled system, the sequence domain impedance equals the phase domain impedance. These definitions lay the basis for the model parametrization derived in the following subsection.

4.2.2 Parametrization: How to Extract the Impedance of a Grid-Connected Photovoltaic System

The model depicted in Figure 4.3 requires the impedance characteristics of both the grid and the connected PV system. These characteristics are different for each grid connection point and system and have to be adapted individually for each system in simulation. Here, the model is adapted to the rooftop PV system described in Subsection 3.1.1. Dedicated impedance measurements were performed to calibrate the model to this system. The same measurements were also evaluated during the root cause analysis in Subsection 3.4.1 and are described there in detail. Two impedance spectra are available: One for the state without the PV system connected to the grid and one when the system is connected.

While Figure 3.25 focuses on the magnitude of the impedance measurement, here Figure 4.4 shows the magnitude and phase angle information of the complex impedances. The frequency resolution of all impedance spectra is 50 Hz. Figure 4.4a shows the magnitude $|Z_{\text{off},p}|$ (upper plot) and phase angle $\varphi_{\text{off},p}$ (lower plot) when the PV system is disconnected. Values for each phase $p = a, b, c$ are plotted separately. The magnitude $|Z_{\text{off},p}|$ in the upper plot increases until it reaches a maximum at 1000 Hz. Afterwards, it decreases and reaches a minimum at roughly 2000 Hz before increasing again at higher frequencies. Except for frequencies above 2000 Hz, the values of all three phases are similar. The corresponding phase angles $\varphi_{\text{off},p}$ in the lower plot are negative around 1000 Hz. At all other frequencies, the phase angles are positive and reach values up to 70° at high frequencies. The phase angle is the same in all three phases, except for frequencies around 2000 Hz.

Figure 4.4b visualizes impedance for when the PV system is active: $Z_{\text{on},p} = |Z_{\text{on},p}| \exp(j\varphi_{\text{on},p})$. In this case, the impedance spectrometer measures the joint impedance of the PV system and the remaining grid. Both magnitude in the upper and phase angle in the lower plot have the same axis scaling as Figure 4.4a for easier comparison. The peak in the magnitude at 1000 Hz

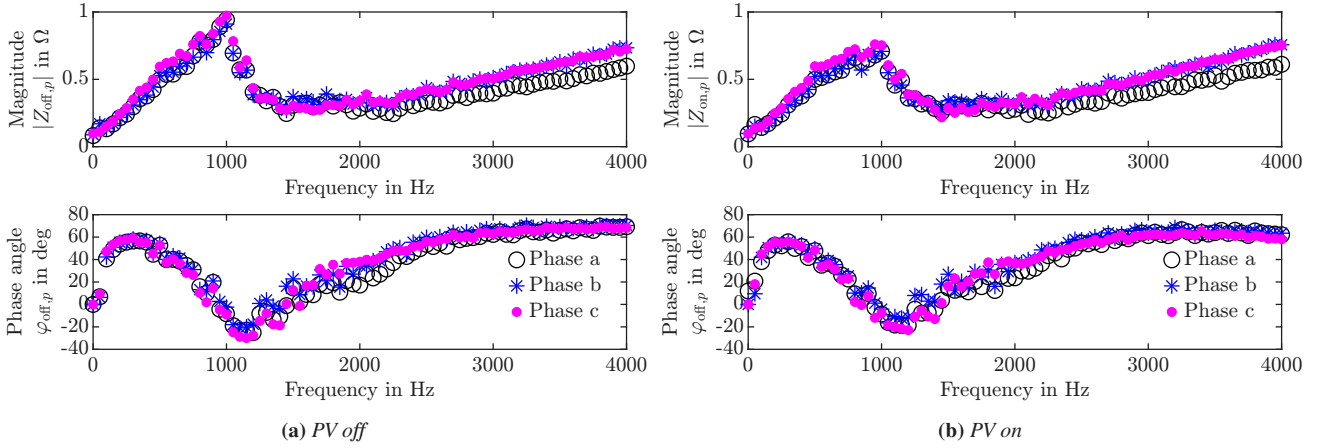


Figure 4.4: Magnitude and phase angle of the measured complex impedance with and without the PV system connected as basis for the data-driven model parametrization.

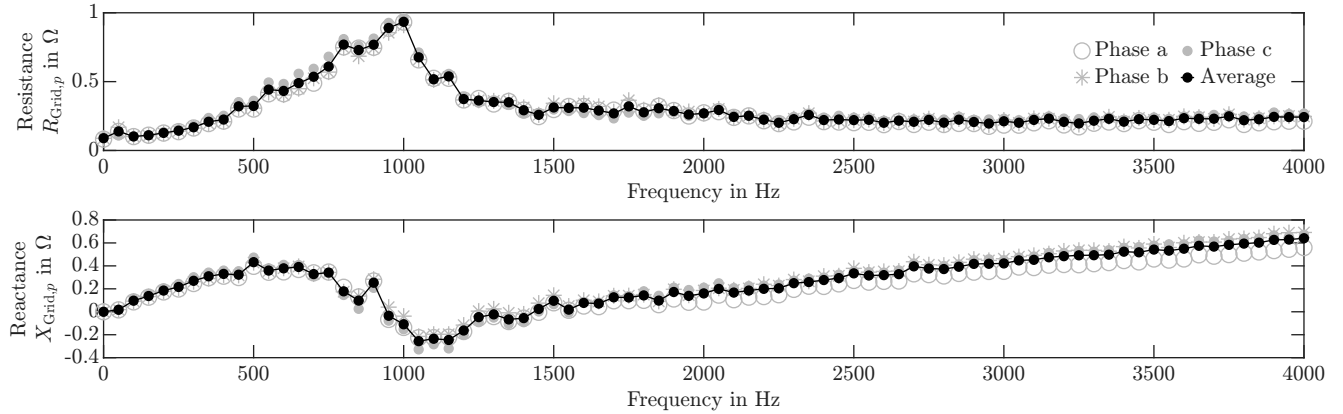


Figure 4.5: Grid resistance and reactance at different frequencies as extracted from the impedance measurement.

is lower compared to the impedance of just the grid (without PV system). The phase angles have similar values in both states (*PV on* and *PV off*).

The impedance for the grid equivalent is set to be the measured impedance when the PV system is not connected in Figure 4.4a: $Z_{\text{Grid},p} = Z_{\text{off},p}$. The data has to be transformed to the PowerFactory format (resistance and reactance in symmetrical components). In detail, the following steps are performed:

1. Transformation to real (resistance $R_{\text{Grid},p}$) and imaginary (reactance $X_{\text{Grid},p}$) parts for each phase p using Eulers formula: $Z_{\text{Grid},p} = R_{\text{Grid},p} + jX_{\text{Grid},p} = |Z_{\text{Grid},p}| \cos \varphi_{\text{Grid},p} + j|Z_{\text{Grid},p}| \sin \varphi_{\text{Grid},p}$. Figure 4.5 shows the resulting resistance $R_{\text{Grid},p}$ and reactance $X_{\text{Grid},p}$ of the grid for all three phases in gray color.
2. Aggregating data of all three phases: The impedance difference between the three phases is small (compare Figure 4.4). For easy transformation, the system is assumed to be balanced. For a balanced system it holds $Z_{\text{Grid},a} = Z_{\text{Grid},b} = Z_{\text{Grid},c} = Z_{\text{Grid}}$. Measured impedances for all three phases $p = a, b, c$ are averaged to estimate the overall impedance Z_{Grid} of a balanced system. Explicitly, the real (resistance) and imaginary (reactance) parts of the impedance are averaged (mean) separately. This average is shown in Figure 4.5 as black dots, connected by lines.
3. Transformation to symmetrical components: According to Equation 4.12 this phase domain impedance $Z_{\text{Grid},p} = R_{\text{Grid}} + jX_{\text{Grid}}$ equals the sequence impedance $Z_{\text{Grid},s}$, if the phases are additionally assumed uncoupled. The resistance and reactance in symmetrical components then equals the phase domain resistance and reactance: $R_{\text{Grid},0} = R_{\text{Grid},1} = R_{\text{Grid},2} = \Re(Z_{\text{Grid}}) = R_{\text{Grid}}$ and $X_{\text{Grid},0} = X_{\text{Grid},1} = X_{\text{Grid},2} = \Im(Z_{\text{Grid}}) = X_{\text{Grid}}$.

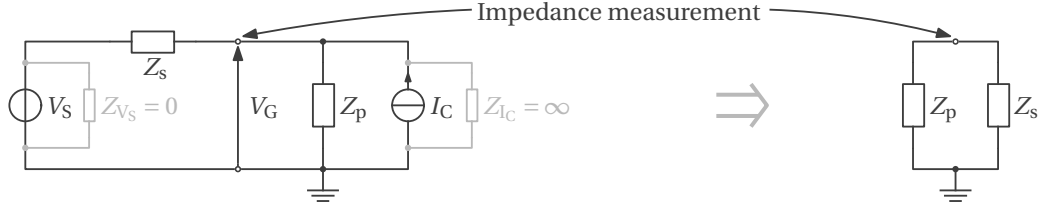


Figure 4.6: Position of impedance measurement device between grid and PV system measures the parallel impedances of both sides.

Extracting the parameters for the PV system is more complex. Only impedance measurements for the combined system (PV and grid) are available. As a grid-following system, no isolated measurement of just the PV system is possible. With some assumptions, this thesis shows how, nonetheless, the inverter impedance can be extracted from the joint measurement: The impedance spectrometer is connected between the PV system and the grid. It measures the joint impedance of both sides: The grid equivalent and the connected PV system. Figure 4.6 shows an equivalent circuit representation of the grid-connected PV system. This representation was introduced in Subsection 4.1.2. The impedance spectrometer is located between the PV and the grid side. The ideal voltage source has zero internal impedance. In contrast, the ideal current source has infinite internal impedance. Following this argumentation, the right side in Figure 4.6 depicts how the impedance spectrometer measures the joint external impedances of the grid and PV system in parallel. This means, the PV impedance Z_{PV} can be calculated from the impedances of the combined system $Z_{\text{Grid and PV}} = Z_{\text{on}}$ and the isolated grid impedance $Z_{\text{Grid}} = Z_{\text{off}}$. The system is still considered balanced. The impedances Z_{on} and Z_{off} are the averages of measurements $Z_{\text{on},p}$ and $Z_{\text{off},p}$ for each phase $p = a, b, c$ individually. It holds

$$\frac{1}{Z_{\text{on}}} = \frac{1}{Z_{\text{off}}} + \frac{1}{Z_{\text{PV}}}, \quad (4.13)$$

transforming this gives

$$Z_{\text{PV}} = \frac{1}{\frac{1}{Z_{\text{on}}} - \frac{1}{Z_{\text{off}}}}. \quad (4.14)$$

For transformation to symmetrical components, the same assumptions as for grid impedance are made (see Equation 4.12). Thus, the impedance is the same in sequence domain $Z_{\text{PV},s} = Z_{\text{PV},p} = Z_{\text{PV}}$.

Power Factor defines the frequency characteristics based on conductance G_{PV} and susceptance B_{PV} , real and imaginary parts of the admittance $Y_{\text{PV}} = G_{\text{PV}} + jB_{\text{PV}}$. In other words, the real and imaginary parts of the inverse impedance:

$$G_{\text{PV}} = \Re\left(\frac{1}{Z_{\text{PV}}}\right) = \frac{R_{\text{PV}}}{R_{\text{PV}}^2 + X_{\text{PV}}^2}, \quad (4.15)$$

$$B_{\text{PV}} = \Im\left(\frac{1}{Z_{\text{PV}}}\right) = -\frac{X_{\text{PV}}}{R_{\text{PV}}^2 + X_{\text{PV}}^2} \quad (4.16)$$

Figure 4.7 shows the resulting values of conductance G_{PV} and susceptance B_{PV} . The underlying data of resistance R_{PV} and reactance X_{PV} are shown as insets for comparison. Both conductance in the upper and susceptance in the lower plot have small values at most frequency components. The conductance at 0 Hz (DC-Component) is -0.8 S. At the fundamental frequency (50 Hz), the conductance is -0.7 S. At all other frequencies, the conductance has smaller absolute values. Around 1000 Hz, it reaches the highest positive values of up to 0.4 S. The susceptance has extreme values at 0 Hz, 50 Hz, and 1550 Hz with -0.7 S, -0.9 S, and -0.7 S, respectively. Based on Equation 4.16, B_{PV} has such larger values, if either X_{PV} is large or the sum $R_{\text{PV}}^2 + X_{\text{PV}}^2$ is small. Around 1000 Hz the susceptance shifts from positive to negative values.

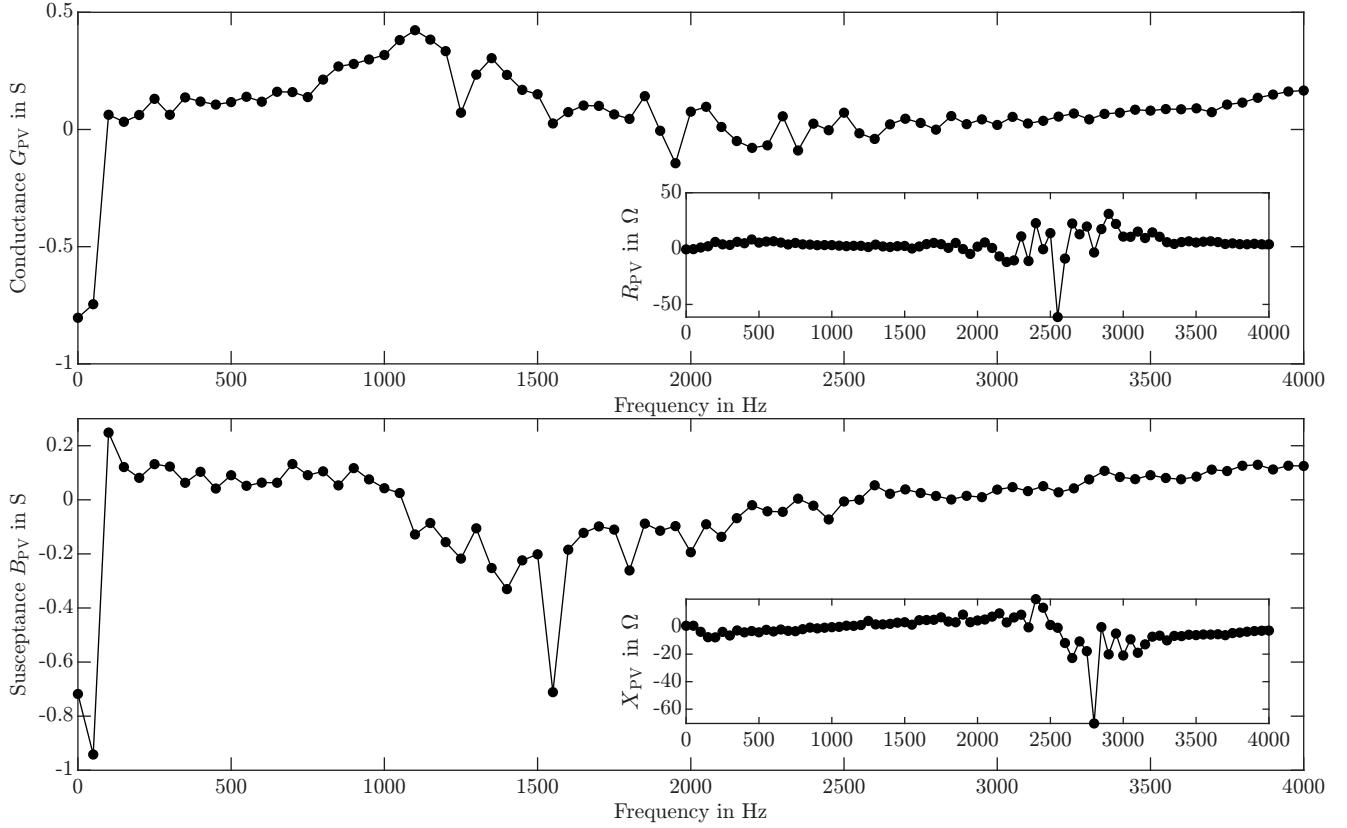


Figure 4.7: Conductance and susceptance of the PV system as extracted from the impedance measurements.

4.2.3 Results: Simulation Agrees with Measurement

This subsection investigates whether the PowerFactory model presented in Subsection 4.2.1 predicts the same voltage waveform alterations in simulation as were observed in the field measurement. To this end, the model is adapted towards the system under investigation (the rooftop PV system) using the parametrization derived in Subsection 4.2.2. Explicitly, for each frequency separately, the series resistance and reactance of the real voltage source are set to grid impedance measurements in Figure 4.5.¹ Similarly, the parallel conductance and susceptance of the real current source are set to the derived PV conductance in Figure 4.7.²

Frequency-domain simulations mean that the calculations are performed for each frequency component separately. The impedance measurements and subsequent model parametrization are available at multiples of the fundamental frequency up to the 80th harmonic (frequency resolution of 50 Hz up to 4000 Hz). No measurements are available at interharmonic frequencies. To simulate the influence of the PV system on voltage distortions similar to the measurement in the field, voltage components at different frequencies have to be present before the PV system is connected. In the model, both the voltage and current source in Figure 4.3 are set to emit the following components:³

- ¹ Within the *AC Voltage Source* component, in the *Power Quality/Harmonics* setting, the tab *Frequency Dependencies* allows to set resistances and reactances using a parameter characteristics of type vector. The characteristic is a vector of resistance/reactance values for a predefined list of frequencies. Each of the three symmetrical components is assigned its own characteristic, but due to the system being balanced, all three contain the same vector.
- ² Within the *AC Current Source* component, in the *Power Quality/Harmonics* setting, the tab *Frequency Dependencies* allows to set conductance and susceptance using a parameter characteristics of type vector. The characteristic is a vector of resistance/reactance values for a predefined list of frequencies. Each of the three symmetrical components is assigned its own characteristic, but due to the system being balanced, all three contain the same vector.
- ³ In the *AC Voltage Source* component, the tab *Harmonic Voltages* within the *Power Quality/Harmonics* settings allows to select a *Harmonic Voltages* element. The type of the *Harmonic Voltages* element is set to *IEC 61000* and defines a list of voltage amplitudes in pu at either integer or non-integer harmonic orders. Both the *AC Current Source* component and the tab *Harmonic Currents* within the *Power Quality/Harmonics* setting allow the selection of a *Harmonic Sources* element. The type of the *Harmonic Sources* element is set to *IEC 61000* and defines a list of current amplitudes in % of the fundamental at either integer or non-integer harmonic orders.

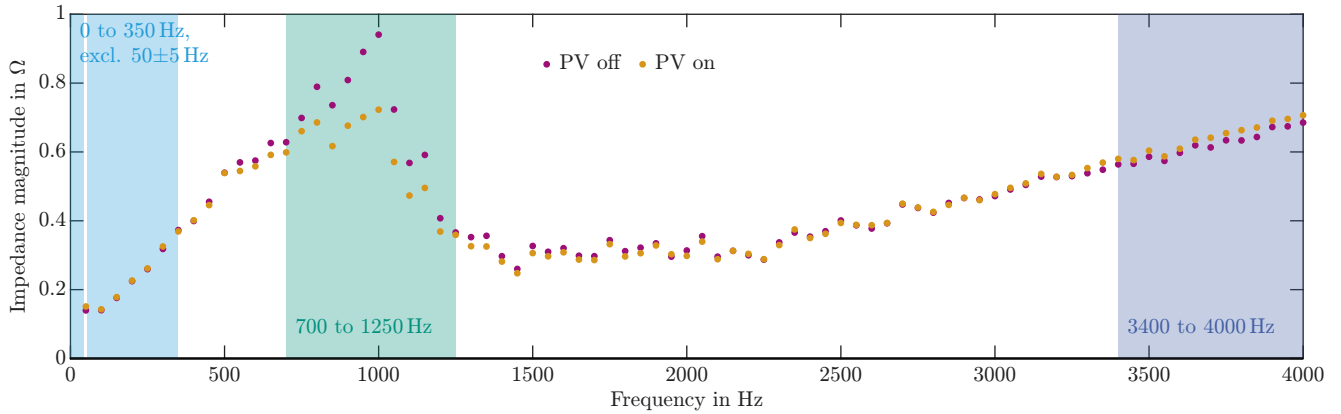


Figure 4.8: Simulated impedance characteristic with and without PV equivalent connected to the grid matches the measured impedance that was used as basis for the model parametrization.

- The grid equivalent acts as a voltage source with amplitude of 1 pu at 50 Hz and amplitudes of 0.001 pu at the frequencies 100 Hz, 150 Hz, 200 Hz, ..., 3950 Hz, 4000 Hz.
- The PV equivalent feeds in a current of 10 A at a frequency of 50 Hz and acts as a current source with amplitudes of 1 % of the fundamental at the frequencies 100 Hz, 150 Hz, 200 Hz, ..., 3950 Hz, 4000 Hz.

These are the same frequencies for which impedance measurements/parameterization are available to avoid PowerFactory from interpolating between the available impedance measurements. This is favorable because the functional development of the impedance curve between measured frequencies remains unclear due to lack of data points. The voltage and current amplitudes are constant over all frequencies except the fundamental 50 Hz. This is a deliberate choice to allow easy observation of changes in the spectrum and is not based on measured voltage and current spectra (in contrast to the impedance that is set based on measurements).

The simulation experiment includes the same steps as used in the real-world measurements: Voltage spectra of the system are calculated first without and then with the PV system connected. The disconnection (and re-connection) is realized by switching off (on) the cubicle that connects the PV system with the terminal. Figure 4.8 shows the network impedance magnitude calculated at the terminal. The values are acquired using the *Frequency Sweep* calculation of the *Power Quality and Harmonic Analysis* in PowerFactory. Data for state *PV on* in orange and *PV off* in purple are directly compared. For both states, the impedance magnitude is largest around 1000 Hz and decreases towards lower and higher frequencies. Above 2000 Hz the impedance magnitude increases again up to 0.7 Ω at 4000 Hz. The most striking difference between the states *PV on* and *PV off* is visible at the impedance magnitude peak around 1000 Hz. If the PV system is disconnected, the impedance magnitude is increased from around 0.7 Hz (*PV on*) to 0.9 Hz (*PV off*).

The network impedance calculations in Figure 4.8 allow a confirmation of the implemented model parametrization. The simulated impedance should equal the measured impedance on which the model parameters are based. For easier comparison, the frequency regions highlighted in Figure 3.25 (measurement results) are also highlighted here in Figure 4.8 (simulation results). The measured impedances (in Figure 3.25) and the simulation results (in Figure 4.8) qualitatively agree over the full spectrum and quantitatively agree at a majority of frequencies. Especially the shift in peak height around 1000 Hz is correctly represented in the simulation. At high frequencies on the right side of the spectrum, the values of measured and simulated impedance differ: While the measured impedance magnitude in Figure 3.25 reaches 0.6 Ω at 4000 Hz, in simulation, the increase reaches 0.7 Ω at the same frequency (see Figure 4.8). This is caused by the fact that Figure 3.25 only shows the impedance measurement of phase a, while for the parametrization, the impedance measurements are averaged over all three phases. At high frequencies, the average over all three phases is larger compared to the measurement on phase a, because phases b and c have higher impedance magnitudes compared to phase a (compare Figure 4.4). Figure 4.8 shows that the impedance parametrization based on measured values was successful. Especially, the approach to extract the isolated impedance of the

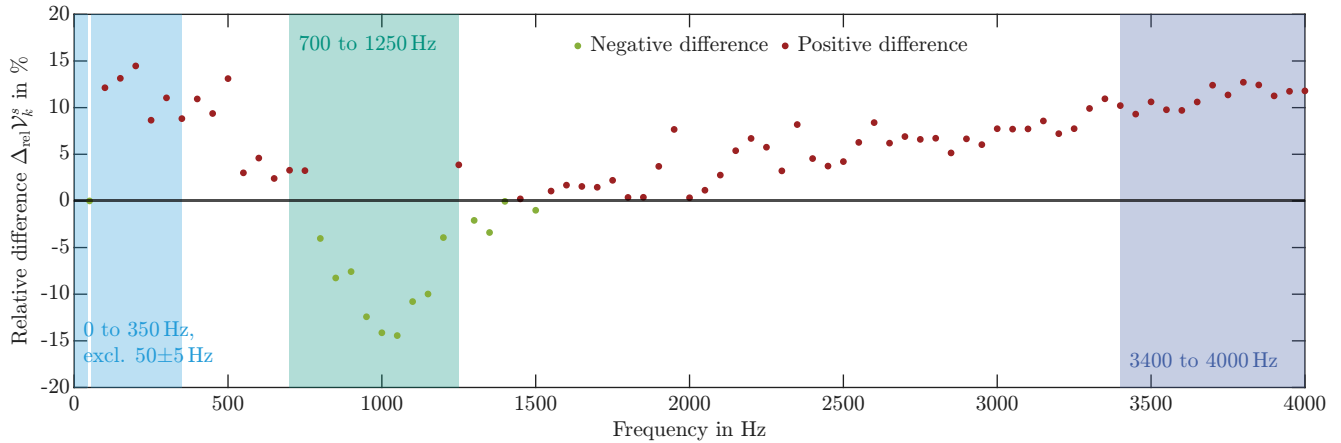


Figure 4.9: Simulated voltage components with and without PV equivalent connected to the grid matches the measured behavior qualitatively.

PV system from joint measurement of the system connected to the grid is found appropriate. The impedance curves for both states *PV on* and *PV off* agree with the measured basis.

In the next step, the capability of the model to capture the frequency-dependent influence of the PV equivalent on the grid voltage components is evaluated. To this end, a harmonic load flow calculation is run in PowerFactory for both system states *PV on* and *PV off*, resulting in two spectra of grid voltage amplitudes. Figure 4.9 shows the change in the voltage components due to the disconnection of the PV equivalent from the model. The relative difference is calculated according to Equation 2.13, same as for measured data. All differences below 800 Hz and above 1500 Hz are positive. This means an increase in amplitude in these frequencies whenever the PV equivalent is connected. The increase reaches values of up to 15 %. In between 800 Hz and 1500 Hz, the difference is negative, meaning that the voltage amplitudes are reduced whenever the PV equivalent is connected. The amplitudes are reduced by up to −15 %.

In comparison, Figure 3.13 shows the change in voltage waveform distortions due to the real-world rooftop PV system during the field measurement. There, three different frequency regions with interesting behavior were identified. These same frequency regions are also highlighted here in Figure 4.9. Simulation and measurement quantitatively agree in the overall characteristic: Both show the reductive influence of the PV on voltage components around 1000 Hz as well as an increasing effect at low and high frequencies. This reductive effect is at the same frequencies as the change in overall impedance due to the PV equivalent in both simulation and measurement. However, the simulation results in Figure 4.9 show values between $\pm 15\%$, while the differences measured in-field in Figure 3.13 range from 20 % down to −40 %. Another difference between measurement and simulation is visible between 1250 Hz and 3400 Hz: While the measured data shows an inconclusive influence of the PV system on voltage components in this frequency range (the median is close to zero, or the percentiles span both negative and positive ranges), the simulated values are clearly positive above 2000 Hz.

Some differences remain between the simulation and the field measurement that could explain the missing quantitative agreement between simulation and measurement. The sources (voltage and current) implemented in the simulation supply constant amplitude over all frequencies, while in the real grid, the spectra are more complex: Different amplitudes are observed, with higher amplitudes at harmonic and lower amplitudes at interharmonic frequencies. The representation of the PV system, grid, and other loads in simulation covers most, but not all, aspects of the complex systems: For example, other loads and generators have nonlinear characteristics that are not represented by the linear impedances in the equivalent circuit.

In summary, the parametrization for the model represents the impedance characteristic of the grid and PV in the model both qualitatively and quantitatively (at most frequencies). The influence of the PV equivalent on the voltage components observed in the field is also represented qualitatively in the model. As a result, the modeling approach and provided parametrization are found to be well-suited to capture the frequency-dependent changes in voltage components due to PV

4.2.4 Summary and Discussion

Due to the highly individual characteristics of grid-connected systems, each installation requires its own model parametrization. This work addresses this challenge by introducing a measurement and analysis approach that enables the extraction of the PV system's impedance characteristics from joint measurements of the system and the grid. The obtained impedance data is subsequently processed and used to parametrize a model in PowerFactory. The resulting model successfully reproduces key aspects of the system behavior. In particular, it captures the impedance characteristics both with and without the PV system connected quantitatively. Additionally, it reflects the change in voltage distortion resulting from the reconnection of the PV system qualitatively, demonstrating its capability to represent the relevant system dynamics.

A major strength of the proposed approach is its applicability under realistic conditions. It eliminates the need for separate laboratory-based system characterization and instead relies solely on in-field measurements. This makes it particularly suitable for practical applications, where isolated testing of grid-connected systems is often not feasible. Furthermore, the method is computationally efficient and does not require any prior knowledge of the internal circuit design or control algorithms of the PV system, aligning well with the black-box modeling necessary for commercial systems. However, several limitations must be acknowledged. As highlighted in [65], classical impedance measurements cannot separate true impedance behavior from source-like characteristics. Thus, the present approach does not allow a separation of impedance-related effects and current source behavior. In addition, impedance measurements were only available at harmonic frequencies, thereby limiting the achievable spectral resolution. The resolution of the parametrized model is directly constrained by the resolution of the underlying measurements. The applicability of the parametrization is further restricted to the specific grid configuration under investigation. Any changes in the grid or the point of connection require a new characterization and model adjustment.

Despite these constraints, the proposed approach proves to be well-suited for the intended application. The combination of straightforward in-field parametrization and high computational efficiency makes the frequency-domain model particularly attractive for large-scale grid studies. It provides a practical means to incorporate realistic system behavior without excessive parametrization effort. Future work could focus on enhancing the methodology to overcome the identified limitations. In particular, differential impedance spectroscopy could be employed to distinguish between impedance and current emission effects. Additionally, translating the frequency-domain representation back into an equivalent time-domain circuit model may extend applicability beyond frequency-domain applications.

In conclusion, the parametrized model based on impedance measurements effectively reproduces the frequency-dependent influence of the PV system on voltage components, confirming the validity of the approach for analyzing distortion-related phenomena in power systems.

4.3 Contributions and Future Work

This chapter transferred the characteristic changes of voltage waveform distortions due to PV systems observed in field measurements into the simulation domain. First, the impedance-based frequency-domain model was identified as the best modeling option for the present application among the multitude of reported PV system modeling approaches. This model consists of a voltage source with series impedance representing the grid and a current source with parallel impedance representing the connected PV system. The analytical calculations based on that model show that the change in voltage components depends on the relative overall impedance with and without the PV system connected. Second, the impedance measurements on the rooftop PV system are used to parametrize the model. The model requires the frequency-dependent impedance for both the grid and PV system separately. However, it is not possible to measure the impedance of the isolated PV installation without grid connection, as it can only operate in grid-following mode. Instead, a method was developed that allows the extraction of the PV system's impedance using two easy-to-obtain impedance measurements: the isolated grid alone and the grid with the PV system connected. The model, parametrized using the impedance measurements, reproduces the frequency-dependent influence of the rooftop PV system on voltage amplitudes at different frequencies. Impedance-related effects of PV systems on voltage spectra are well captured in frequency-domain equivalent models. The modeling approach

and parametrization developed in this thesis can now be used to incorporate the correct impedance behavior of PV systems in larger grid studies by adding more PV equivalents. It can then be used to investigate the interaction of systems with each other or the effect of an increasing number of installed systems in the grid.

Naturally, the presented model is still an approximation of the real world. To further approach the complexity of the real system, the model could be extended with additional impedances. In addition, replacing the ideal current source with a dependent current source would include more control-related effects of the system. Using the more complex differential impedance spectroscopy instead of classical impedance measurement allows for fully separating passive impedance-related effects and active current sources [65]. This approach would allow parameterizing both the impedance and current source parameters. However, it would have to be adapted to the present case, where an isolated measurement on just the PV system without the public grid connected is not possible. Further down the line, it might become interesting to transfer the frequency-domain simulation back to the time domain. Because the internal circuit and control scheme of the installations are unknown, an equivalent-circuit approach can be used to compute a network equivalent (a combination of passive components that reproduces the exact impedance measurement) from the impedance characteristic. Matlab functions such as `Zfit` can be used for this [193].

5 Conclusion and Future Work

PV systems play a prominent role in the energy transition. However, the actual influence that PV installations have on voltage distortions remained unclear. Available reports are inconclusive; they report either increased, decreased, or unaffected voltage distortions in the context of PV installations. These investigations focus on THD_V and lack spectral depth. In addition, the effects were not clearly attributed to the respective systems under investigation.

Based on the identified research gap, this thesis addresses one main question: **How do PV systems affect voltage waveform distortions at different frequencies?** The three related sub-questions can now be answered:

- **How can the influence of a PV system be identified and separated from that of other loads and generators?** This thesis provides an innovative field measurement method that quantifies changes in voltage waveform distortions in the public distribution grid caused by a PV system. The method is based on repeatedly comparing voltage distortions with and without the system under investigation connected to the grid. It directly attributes the observed effects to the investigated system. The required spectral depth is addressed with a dedicated analysis based on FFT. Due to the method's easy and low-cost accessibility, it can be used for widespread studies across multiple commercial PV installations and other IBR. Based on this first contribution, it is now possible to assess the actual influence of PV systems on voltage distortions in-field in high spectral resolution.
- **How do different in-field PV systems change voltage distortions on a spectral level?** The second contribution of this thesis are empirical field studies conducted at three different PV systems of varying size, inverter manufacturers, and grid compositions. The influence of the PV installation on voltage waveform distortions is found to be frequency-sensitive, installation-specific, and strongly influenced by the connected grid's characteristics. Explicitly, a specific PV system can simultaneously increase, decrease, or not affect voltage distortions, depending on the frequency of each distortion in the spectrum. The frequency dependence looks different for each of the investigated systems. In addition, the same system connected to two different grid compositions shows two distinct frequency dependencies. The additionally conducted root-cause analysis attributes the observed changes in voltage distortions to the grid-side hardware filter of the PV inverter. This filter mainly contributes to the PV system's impedance characteristic, which, in relation to the present grid impedance, causes the observed changes in voltage distortions. These complex frequency-dependent and system-specific characteristics are impossible to grasp in aggregated total distortion indices used in prior works. In addition, the PV installation and its connected grid have to be treated as a joint system that determines the overall effects based on their relative impedance characteristics. Each combined system (PV and grid) must be characterized individually.
- **How can the change in voltage distortions due to the PV system be represented in models?** Frequency-domain impedance-based equivalent models are identified as best suited to capture the observed complex frequency-dependence among the multitude of PV system models. They allow high frequency resolution without requiring too much computational effort. Specialization of the model to a specific system requires impedance measurements. Because grid-connected installations are difficult to analyze in terms of their isolated impedance characteristics, this thesis presents a new parametrization method based on comparative impedance measurements. The model, adapted to a specific installation based on the new parametrization approach, reproduces the frequency-dependent influence of the system on voltage waveform distortions. With this final contribution, a model is now available that can incorporate the frequency-sensitive effect of PV systems on voltage waveforms in simulation. The related parameterization approach allows to easily adapt the model to each PV installation individually to account for the diverse nature of the effects.

Overall, this thesis proves that no generalized or aggregated assessment is possible on how PV systems influence grid voltage distortions due to the individuality in behavior. If and how a voltage distortion at a certain frequency is influenced due to the presence of a PV installation is an individual, frequency-dependent characteristic that is different for each system at its grid-connection point. These complex and diverse characteristics can be quantified and included in simulations using the methods contributed in this thesis.

The presented model lays the foundation for larger grid studies that take the individual behavior of each system into account. For the future, this thesis proposes to use the voltage-measurement-based system characterization directly for the parametrization of the model instead of impedance measurements in future work. This would allow an even easier model parametrization. However, such an approach would have to be carefully designed to not impair the accuracy of extracted parameters, and assumptions on, e.g., the grid impedance will have to be made. In the future, the sheer number and multitude of PV systems connected to the grid will call for a full automation of this characterization process. To achieve this, this thesis suggests exploiting the internal measurements within the inverter. These are necessary anyway to synchronize the current output with the frequency and phase angle of the connected grid. Based on the method developed in this thesis, the analysis would look as follows: Two short snippets of the captured grid voltage waveform data (one before and one after the system connects the hardware filter and starts the power feed-in) are transferred to the frequency domain. Subsequently, after comparison of the distortions with and without operating the inverter, the PV system's individual frequency-dependent influence on voltage waveform distortions can be characterized for its current grid connection point. Such a characterization could be automatically performed when the system is first connected to the grid, or better yet, routinely throughout the year.

Overall, this will allow a fully automated model parametrization of each PV system in the grid. The resulting model is then capable of assessing voltage distortion behavior in large-scale grid studies. Based on the model, PV system design can be optimized towards its effects on distortions, for example, exploiting the reductive influence on distortions as a new and additional grid-supporting service offered by IBR. As such, this work lays the groundwork for a future, climate-neutral energy system in which PV installations contribute towards a stable, renewable, and high-quality power supply.

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Declaration on the Use of Generative Artificial Intelligence

I declare that I have prepared this dissertation independently and that all scientific ideas, research questions, methodological decisions, analyses, interpretations, evaluations, and conclusions presented in this work are my own. I further declare that I assume full responsibility for all content contained in this dissertation, including content created or revised with the assistance of software tools and generative artificial intelligence systems. In accordance with the guidance of the KIT Faculty of Electrical Engineering and Information Technology regarding the use of generative artificial intelligence in scientific work, I transparently document the use of Artificial Intelligence (AI)-supported tools during the preparation of this dissertation. All outputs generated by such systems were critically reviewed, verified against sources where applicable, and extensively revised before inclusion. Generative AI was used exclusively as a supporting tool and not as a substitute for scientific reasoning, literature evaluation, experimental work, data analysis, interpretation of results, or the derivation of conclusions.

Tool / Model	Purpose of Use	Affected Sections	Typical Prompt Type	Post-Editing by Author
Microsoft Copilot (GPT-5)	Preparation of this declaration page based on a list of used tools	This declaration Chapter 5 only	Generate a declaration documenting AI usage in a dissertation according to university requirements	Extensive revision and verification
	Structuring of content based on lists in outline, discussion and summary parts, including suggestions for wording and readability improvements	Sections 1.3, 2.2.3, 2.3.3, 2.4.3, 3.1.4, 3.2.3, 3.3.3, 3.4.4, 4.1.3, 4.2.4, 2.5, 3.5, 4.3	Suggest alternative structures for sections based on extensive lists provided by author and suggest alternative wording to improve understandability	Extensive revision and independent adaptation
	Transformation of author-written publication content into bullet-point summaries to support completeness checks	Sections 2.2.2, 2.4.1 and 3.2.1	Summarize the key findings and methodological steps of the following publication as bullet points	Final text written by author
Grammarly Free version 8.937.0	Grammar, spelling, punctuation, style improvements	Entire manuscript (since Oct. 2024)	Automated grammar and style suggestions	Accepted selectively after manual review
DeepL	Translation of the Abstract to the German Kurzfassung	“Kurzfassung” Chapter	Sequential translation of paragraphs	Extensive revision and final author wording
SciSpace, Perplexity, Elicit, Connected Papers, Research Rabbit	Identification of potentially relevant literature, additional references and related work based on keywords and provided publication lists from database searches	Literature reviews in Section 1.1 and Subsection 4.1.1	Suggest literature related to topic of PV field-studies and modeling and explore related publications starting from an individual paper or list of papers	Sources independently checked and selected

No generative AI system was used to generate research data, modify experimental results, perform scientific evaluations without verification, or derive the scientific conclusions of this dissertation. All reported results, interpretations, and conclusions were produced and validated by the author.

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A Appendix

A.1 Spectral Analysis Has Larger Amplitude Errors in Case of Smaller Fourier Window

Subsection 2.3.2 validates the accuracy of the waveform analysis applied in this thesis. The used validation routine is described in detail there. It concludes that while the absolute amplitude error increases towards higher frequencies, differential changes in amplitude are detected with high accuracy at all frequencies (compare Figure 2.6 and Figure 2.7). However, only the analysis in a time resolution (Fourier window) of 1 s is validated. Here, an identical investigation for the other available time resolutions (200 ms and 100 ms) is presented. This allows comparison of different time resolutions in terms of their suitability for the analysis and the selection of the best option for the application in this thesis. The analysis includes both the harmonic and interharmonic test cases defined in Equation 2.7 and Equation 2.8.

Figure A.1 presents the resulting amplitude errors as defined in Equation 2.6. Both time resolutions in Figure A.1a and Figure A.1b show the following characteristics: At all frequencies, the amplitude is underestimated in the processed data (negative relative error Δc_k). At higher frequencies, larger errors are visible. The interharmonic test case shows considerably larger errors compared to the harmonic test case. This so-called picked-fence effect (compare Subsection 2.2.1) is due to the bin matching explained in Figure 2.5. The larger the mismatch between the test signal component and the processed frequency bin, the larger the resulting estimation error. The maximum error for 100 ms time resolution in Figure A.1b is significantly larger compared to 1 s resolution in Figure 2.6. This is mainly caused by reduced frequency resolution, leading to a larger potential mismatch between test signal components and processed spectral bins. In addition, components close together (relative to the extracted bins) increase the error because their content leaks into neighboring bins.

According to Figure 2.7, changes in distortion amplitude are detected with high accuracy (error below 0.1 %) in the case of a Fourier window of 1 s. Figure A.2 shows the error of amplitude change detection (compare Equation 2.11) for higher time resolutions (Fourier window 200 ms and 100 ms). While the errors are a little larger compared to 1 s resolution, they remain below 0.5 % at almost all frequencies.

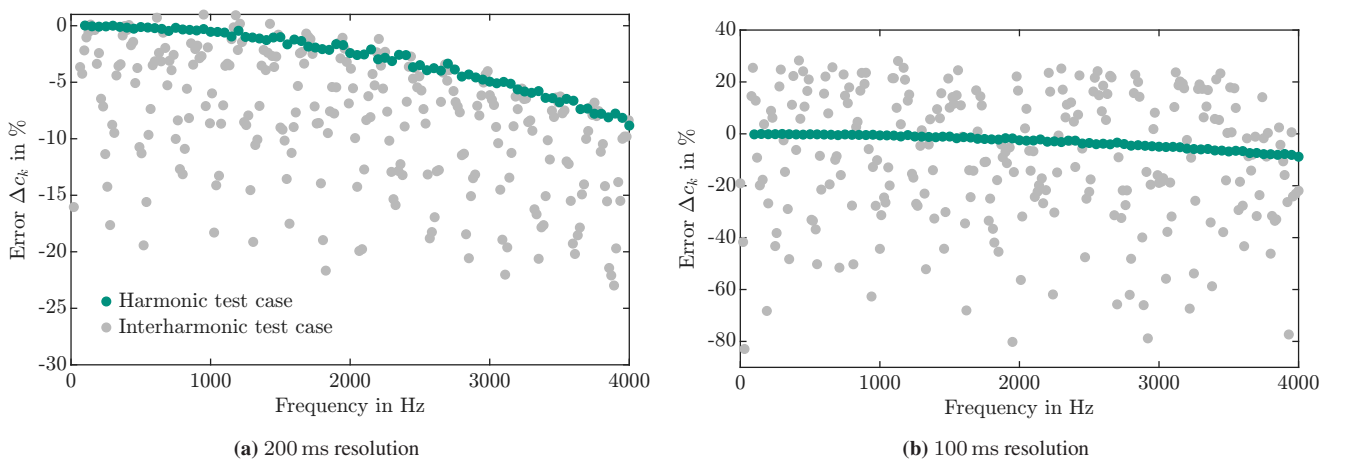


Figure A.1: Amplitude estimation error for smaller Fourier windows of 200 ms and 100 ms also increases with frequency but is larger compared to 1 s window.

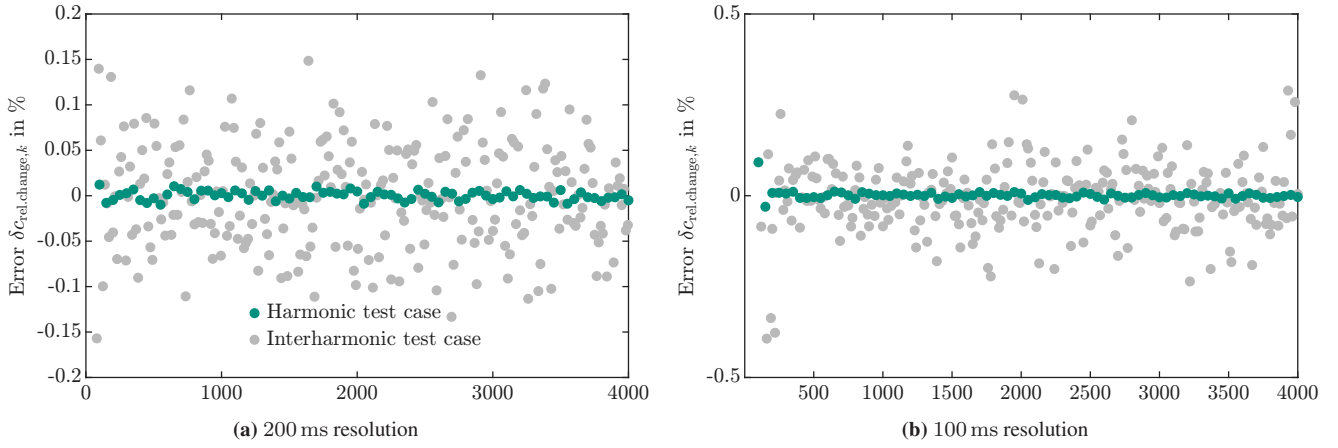


Figure A.2: Error in detecting changes in distortion amplitudes for higher time resolutions are larger compared to 1 s resolution but remain below 0.5 %.

Overall, absolute distortion amplitudes are detected with potentially high errors, especially for the higher time resolutions presented in this section. Changes in distortion amplitude also have larger errors for higher time resolutions. However, for 200 ms and 100 ms Fourier windows the amplitude change detection errors still remain below 0.5 % at all frequencies. As a result, the spectral analysis is capable of detecting variations in voltage distortion amplitudes with high accuracy in all time resolutions.

A.2 Distortion Phase Angle Error Has the Same Characteristics in all Time Resolutions

Subsection 2.3.2 presents the accuracy of phase angle estimates of the spectral analysis described in Section 2.2. The analysis in 1 s resolution is presented there. This section presents additional analysis of the higher time resolution.

Figure A.3 presents the phase angle error as defined in Equation 2.12. The data is based on the harmonic test case defined in Equation 2.7 and the interharmonic test case defined in Equation 2.8. With a 200 ms Fourier window, the validation routine gives the absolute phase angle errors (defined in Equation 2.12 shown in Figure A.3a, while Figure A.3b shows the results of the 100 ms time resolution. Same as in 1 s resolution (compare Figure 2.8), the error for harmonic distortions remains close to

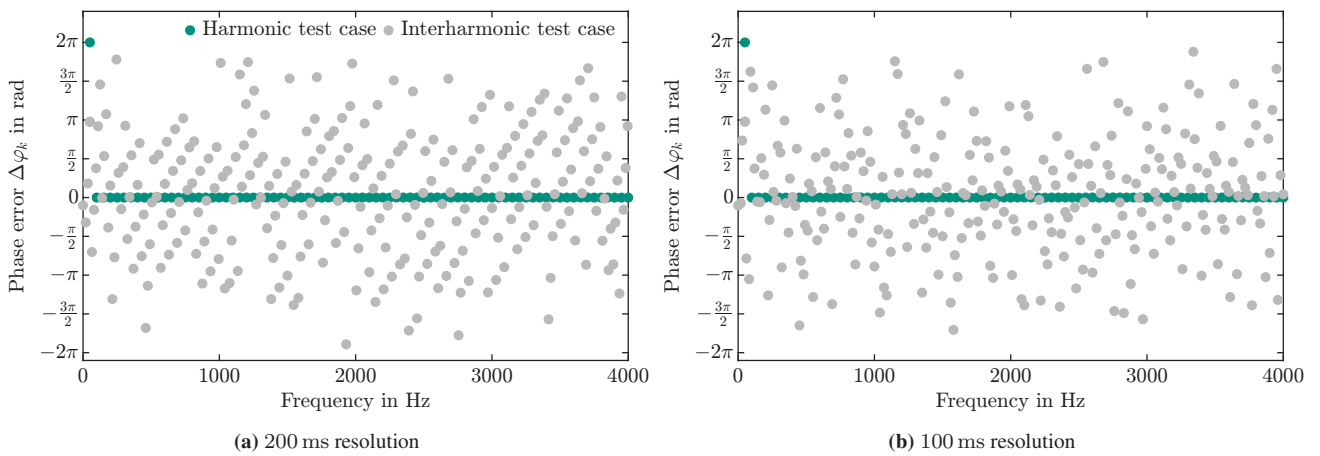


Figure A.3: Distortion phase angle estimation error for 200 and 100 ms Fourier window shows the same behavior as the 1 s Fourier window.

zero at all frequencies. At interharmonic frequencies, the phase angle errors take all values from -2π to 2π . This was already observed for the 1 s Fourier windows in Figure 2.8 and is attributed to the picked-fence effect. For harmonic frequencies, the time resolution does not influence the accuracy of the extracted phase angles.

A.3 Identical Behavior in all Three Phases

Subsection 3.2.1 presents how the rooftop PV system described in Subsection 3.1.1 influences voltage distortions in a single phase. This section presents the results for the other two phases of the three-phase measurement.

Figure A.4 depicts the differences of the absolute distortion spectra $\mathcal{V}_{k,\text{on/off},p}^s(t)$ for all three phases $p = a, b, c$ between the two states with and without the PV system connected to the grid. All three phases share the following distortion characteristics: The spectra have the largest amplitudes at odd harmonic frequencies, and distortion amplitudes decrease towards higher frequencies. However, small differences between the phases are observed at individual distortion components. For example, the amplitude of the 9th harmonic (450 Hz) is smaller in phase a compared to the other two phases. The difference in the amplitude of distortions from one phase to the next is due to the variation in loads connected to each phase. Most loads in the office building underneath the PV system are connected to a single phase only. As a result, they cause an imbalance in distortions between the phases. But as shown in Figure A.4, the differences are so small that they are hardly visible in the overall complex amplitude spectra.

Because the impact of the PV system is difficult to discern in Figure A.4, Figure A.5 shows the relative difference Δ_{rel} between the two states *PV on* and *PV off*. Δ_{rel} is defined in Equation 2.13. Figure A.5 shows the medians and percentiles of all 80 available shutdowns. The analysis is identical for all three phases and was applied to a single phase in Subsection 2.4.1 and Subsection 3.2.1. A positive difference means that the distortion amplitudes at these frequencies are larger whenever the PV system is connected to the grid (red data points in Figure A.5). If the presence of the PV system causes reduced distortion amplitude at a specific frequency, the difference is negative (green in the figure). All three phases show the same overall characteristic: The medians follow a distinct band, but individual frequency components diverge outside of the band. The 5 % to 95 % percentiles follow the behavior of the band, with the largest dispersion at low and high frequencies. Below 500 Hz and above 3000 Hz, the differences are positive, but with a wide percentile range. A strong decrease of distortions between 750 Hz to 1250 Hz of more than 10 % is apparent in all three phases. The phases differ mostly in the individual frequencies that lie outside of the band. Which and how far individual components diverge from the band is different in each phase. For example, Figure A.5c shows a positive median difference at 1050 Hz while Figure A.5a and Figure A.5b do not. The range of percentiles is also different. For example, at frequencies around 1750 Hz, the percentiles spread wider in Figure A.5c as compared to the other two phases.

Overall, the positive effect of the PV system on voltage waveform distortions is observed in all three phases in the same way, even though the distortions vary slightly from phase to phase due to the different loads present.

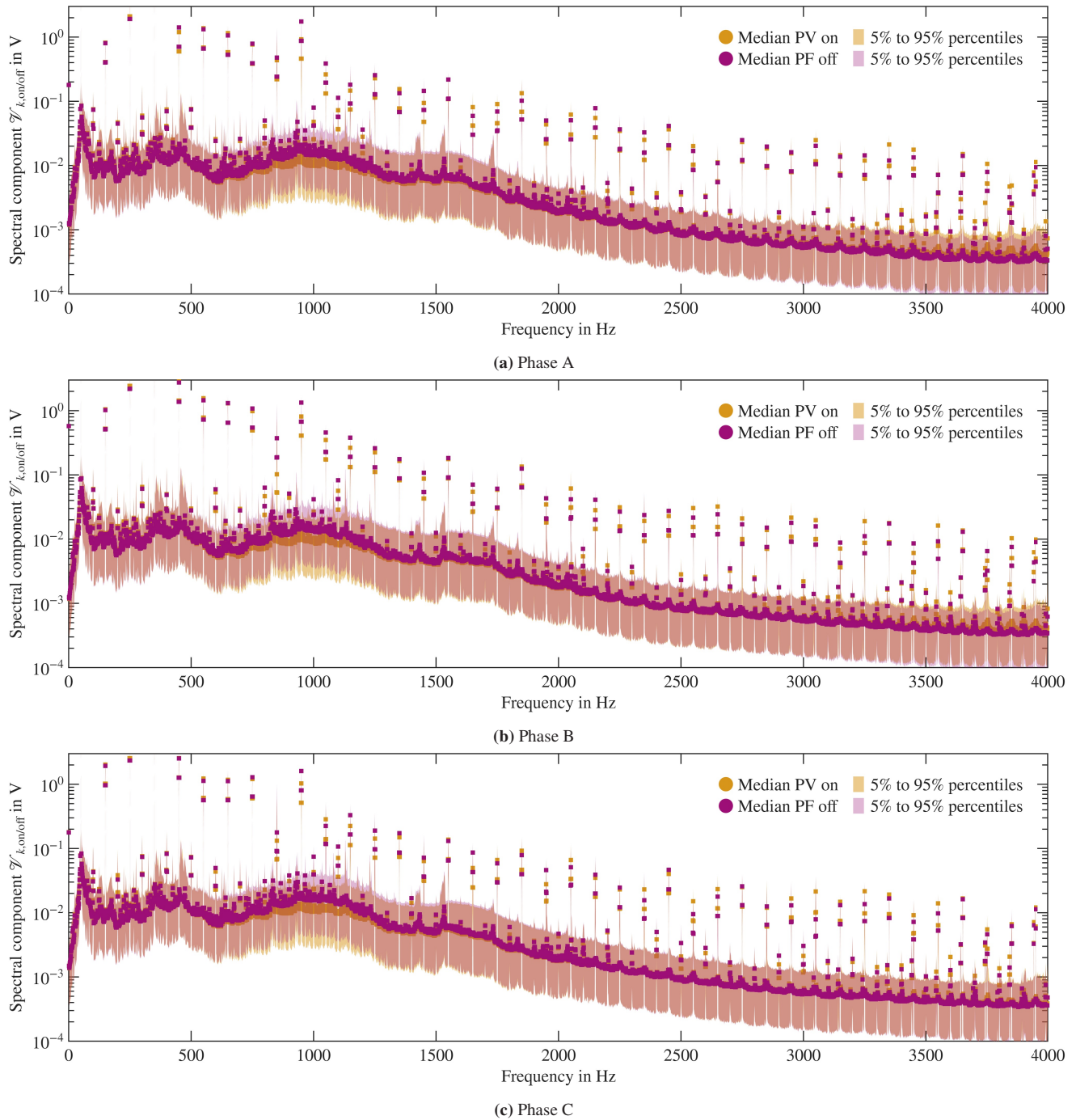


Figure A.4: Voltage distortions in all three phases at the rooftop PV have similar composition, and the influence of the system is difficult to discern. Figure A.4a is identical to Figure 3.12 and is here shown again for comparison.

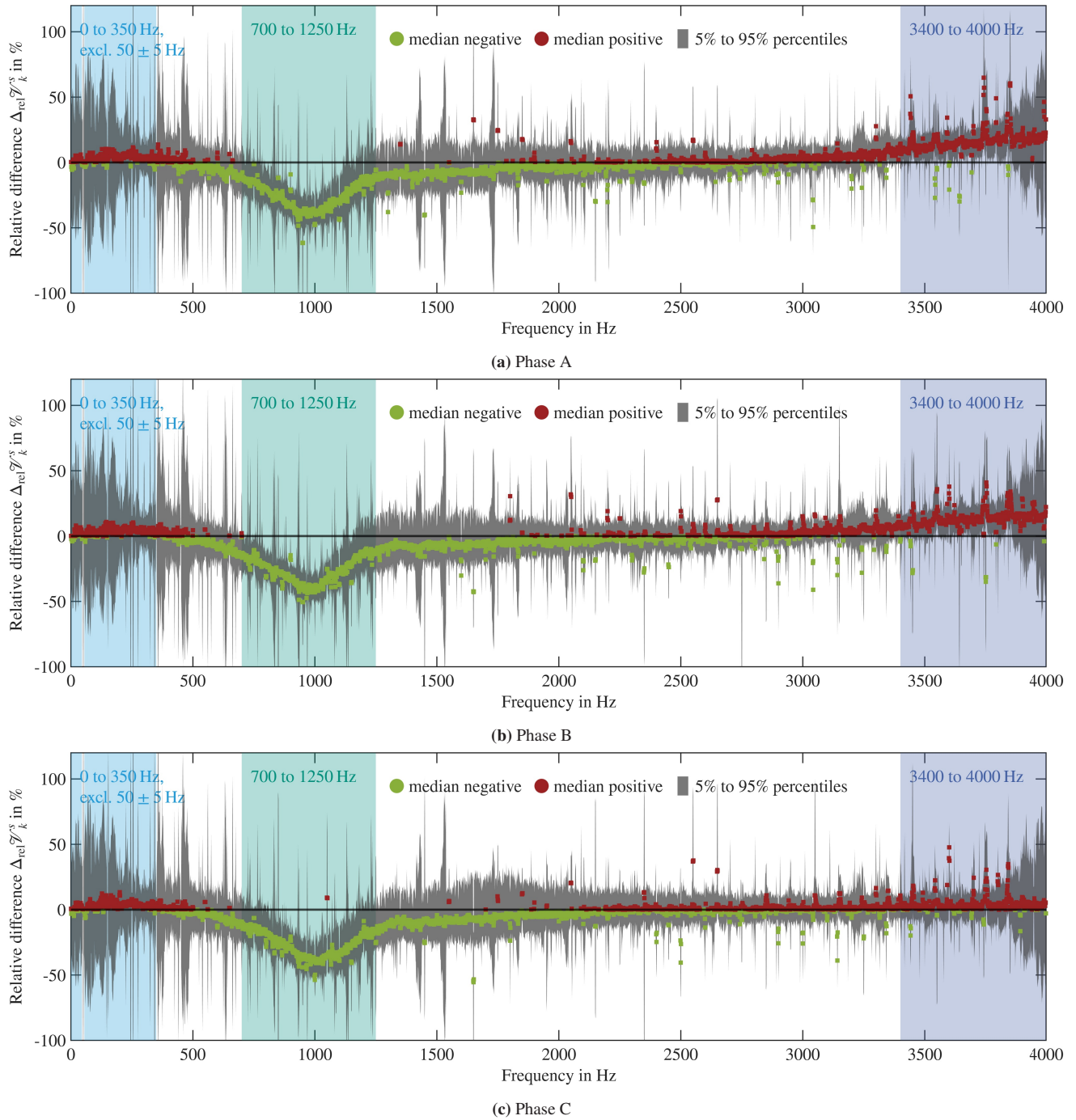


Figure A.5: Relative change in voltage distortions in all three phases due to the rooftop PV system shows the same characteristic in all three phases. Figure A.5a is identical to Figure 3.13 and here shown again for easier comparison.

A.4 Different Behavior at low Frequencies on Weekday Compared to Weekend Day

Subsection 3.2.1 presents how the rooftop PV system described in Subsection 3.1.1 influences voltage distortions. The underlying experiments were conducted on the 20th and 21st of September, 2024. This corresponds to Friday, a weekday, and Saturday, a weekend day. During the weekend (Saturday, Sunday), the office building underneath the rooftop PV system is completely abandoned. However, servers, batteries, heating/cooling systems, and some computers are still running. This section investigates whether this difference in usage and thus load composition influences voltage distortions and the impact of the PV system.

Figure A.6 compares the distortion spectra $\mathcal{V}_{k,\text{on/off},p}^s(t)$ for the two measurement days separately. The median and percentiles of all available spectra of phase a are visualized. On both days, the harmonic components are larger compared to interharmonic frequencies. Harmonic and interharmonic amplitudes decrease towards higher frequencies on both days. Only a few individual components look different on the weekday compared to the weekend day. For example, at 3350 Hz the amplitude difference between the two states *PV on* and *PV off* is much larger on the Friday compared to the Saturday (on this day the medians of both states lie on top of each other).

Figure A.7a and Figure A.7b show the relative differences between the spectra in Figure A.7. For each plot, the shutdowns occurring on that day are analyzed. There are 40 shutdowns per day. Both days show many similarities: The median differences are positive at low and high frequencies and negative at median frequencies. The identified reductive impact of the PV system on voltage distortions between 750 Hz to 1250 Hz is similar on both days. At the same time, small differences between the days exist: There is a larger positive average difference on Friday at frequencies below 500 Hz. On the weekday, the shutdown of the PV system causes a larger increase in voltage waveform distortions. The percentiles at frequencies above 3800 Hz span a wider range on Friday compared to Saturday. How far and which individual components divert from the overall band of medians also depends on the day. For example, the high positive median (45 %) at 1650 Hz on Friday in Figure A.7a is only 26 % on Saturday (compare Figure A.7b).

Overall, the reductive impact of the PV system on medium frequency distortions is identical on both days. Only small frequencies below 500 Hz show a dependence on the measurement day.

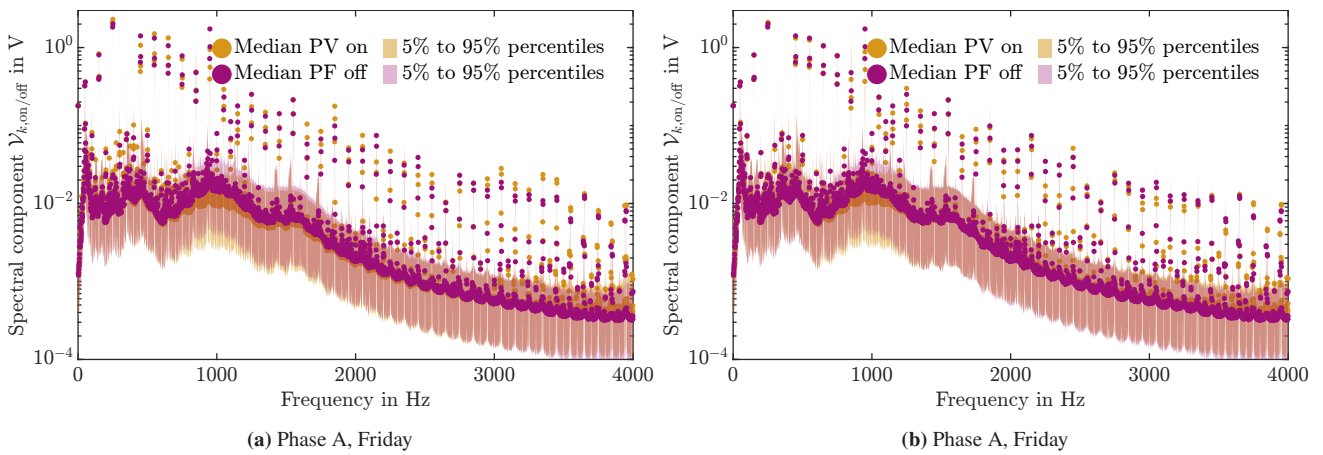


Figure A.6: Voltage distortion on two different days at the rooftop PV system shows the same composition on both the weekday (Friday) and weekend day (Saturday).

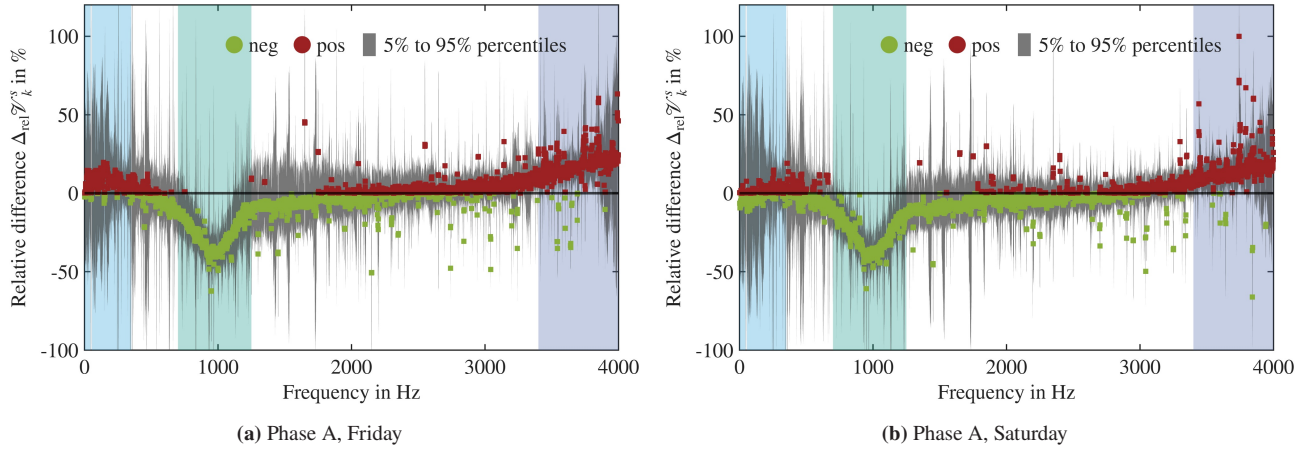


Figure A.7: Relative change in voltage distortions on two different days due to the rooftop PV system shows a difference in behavior between work day (Friday) and weekend day (Saturday) at very low frequencies.

A.5 Various Days Agree in Overall Volatility of Distortions

Subsection 3.2.2 investigates the PV system described in Subsection 3.1.1 using the non-intrusive method introduced in Subsection 2.4.2. Figure 3.15 shows the spectrogram of voltage distortions at the PV system under investigation on the 25th of May, 2024. The distortion volatility observed there is the basis for the selected analysis time range of $\Delta t_{\text{meas}} = 30$ min.

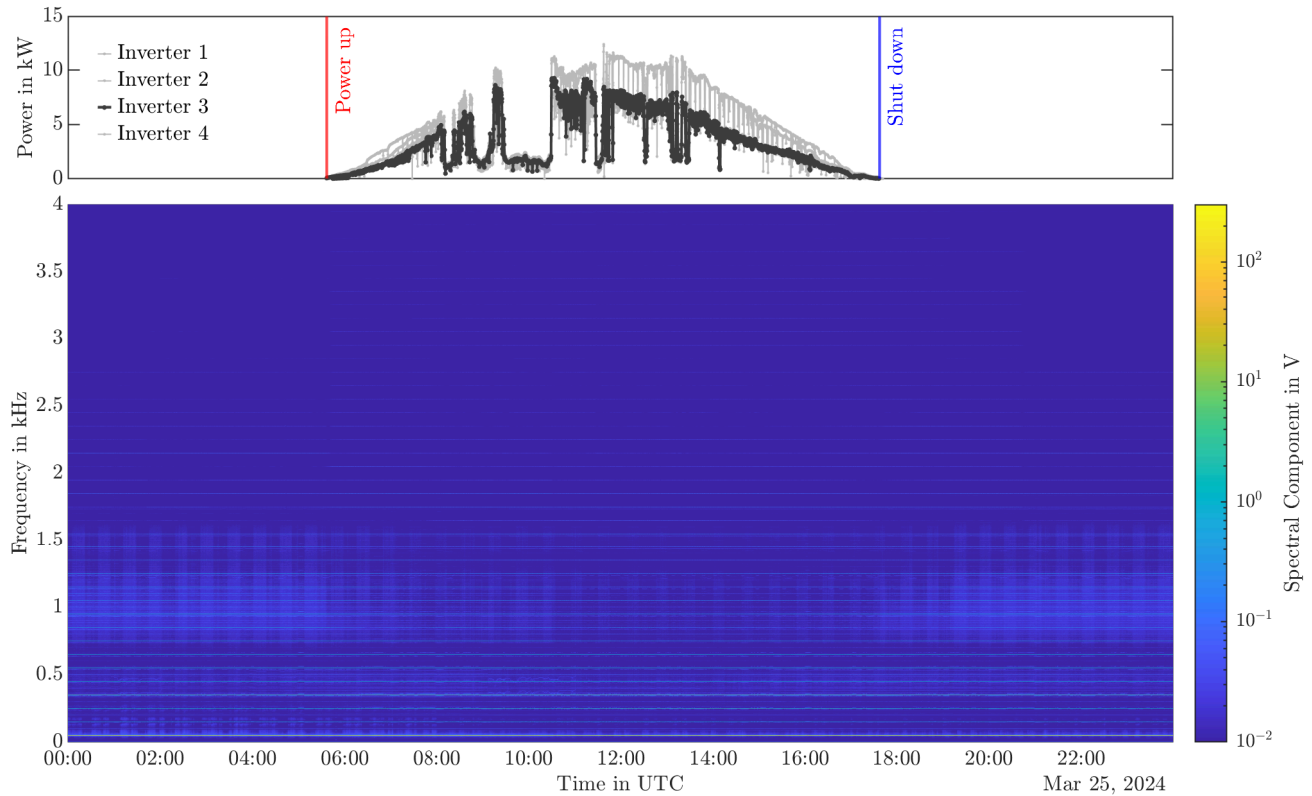


Figure A.8: Spectrogram measured at the rooftop PV system on the 25th of March, 2024, in the lower plot, together with the PV power on that day (upper plot). The distortions around 1 kHz and below 0.5 kHz fluctuate with time (approximately every 15 min) and are reduced during the day.

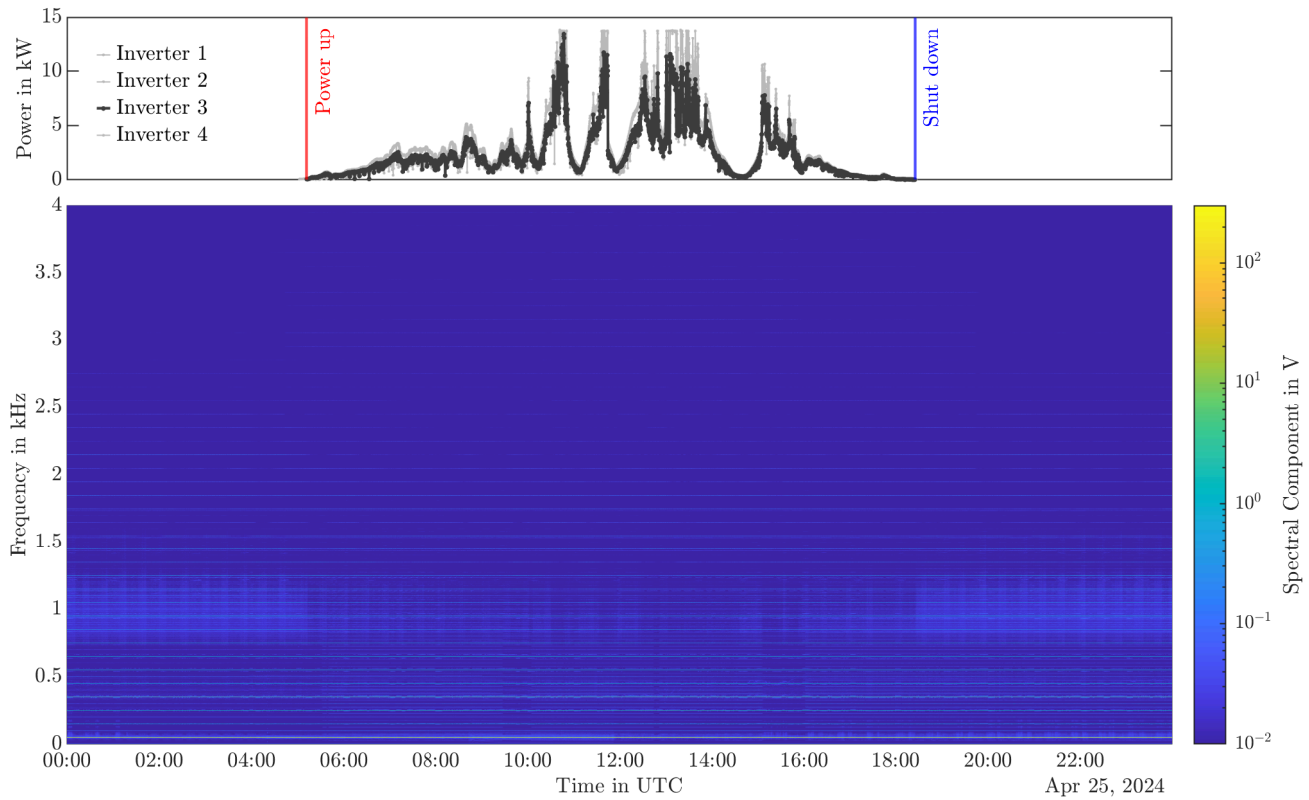


Figure A.9: Spectrogram measured at the rooftop PV system on the 25th of April, 2024, in the lower plot, together with the PV power on that day (upper plot). The distortions around 1 kHz fluctuate with time (approximately every 15 min) and are reduced during the day.

Several more days are being investigated for their distortion composition and their time evolution. Figure A.8 through Figure A.11 show depictions similar to Figure 3.15 but with data from the 25th of March, 25th of April, 25th of July, and 25th of December, 2024. This includes different days all over the year and, especially, in different seasons.

Overall, the different days show either similar variations in distortion over time or mostly the same distortion composition throughout the day or night, respectively. The reduction of distortions around 1 kHz is visible on all days, but the duration of the reduction, caused by the power-up and shutdown of the system, shows seasonal changes according to daylight duration.

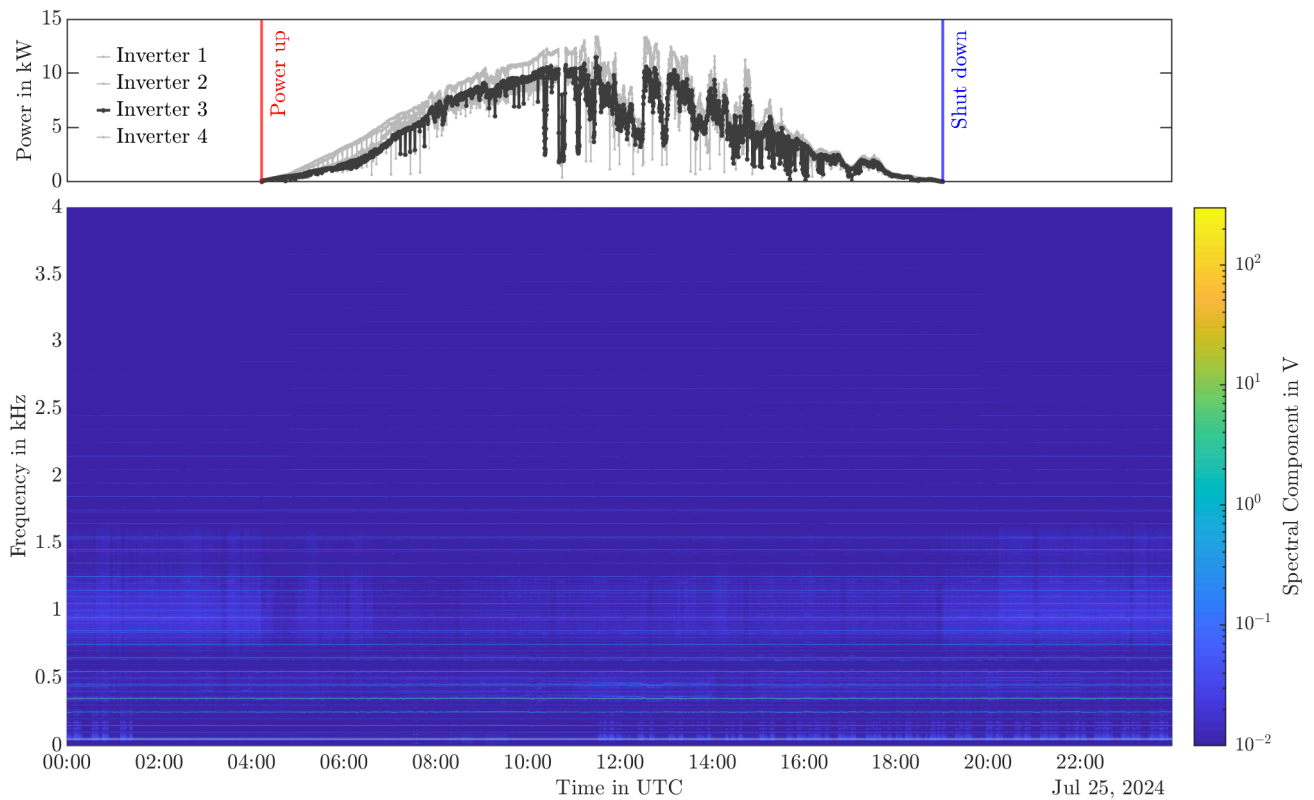


Figure A.10: Spectrogram measured at the rooftop PV system on the 25th of July, 2024, in the lower plot, together with the PV power on that day (upper plot). The distortions do not change much during the day and night, respectively, but are reduced during the day around 1 kHz.

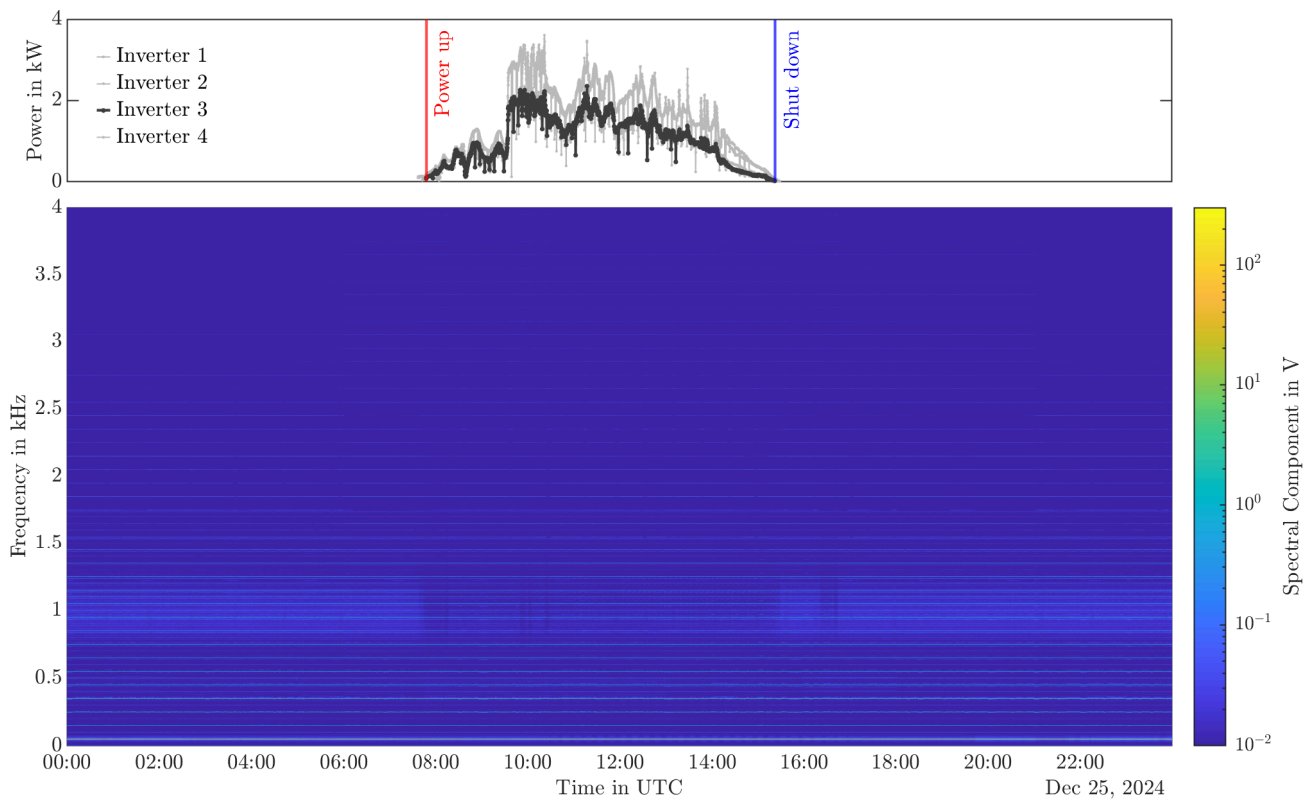


Figure A.11: Spectrogram measured at the rooftop PV system on the 25th of December, 2024, in the lower plot, together with the PV power on that day (upper plot). The distortions do not change much during the day and night, respectively, but are reduced during the day around 1 kHz. The daylight duration is significantly reduced due to the winter season compared to, e.g., Figure A.10.

A.6 Scatter Plots Attribute Correlations to Difference Between Distortions With and Without the Photovoltaic System

Subsection 3.4.2 investigates the power dependence of voltage distortions using Pearson correlation. It concludes that the distortions are not correlated with the inverter power. They are only influenced by the PV system disconnecting or reconnecting to the grid, but not by power variations during operation. This appendix section further investigates the correlation coefficients using scatter plots between individual distortion amplitudes at a single frequency and the inverter power. Instead of investigating all 4000 distortion components, several frequencies with interesting behavior are selected and presented here.

Figure A.12a on the left-hand side of Figure A.12 looks at the voltage distortion at 1000 Hz. 1000 Hz is the center of the frequency region with moderate negative correlation. This harmonic shows a Pearson correlation coefficient of -0.60 with the full power time series that includes the times with deactivated PV system (compare Figure 3.28). The distortion amplitude time series for every single frequency is plotted versus the time-dependent power measurements. Whenever the PV system is disconnected, the power is zero (points in red color). When the system is connected, different power values are reached, and the data points are black. The scatter plot shows that while the distortion amplitudes are distributed over a broad range from 0 to 0.05 volt, they do not change with power; all points remain in the same range at all powers. Only the red points at zero power during a disconnected PV system show a broader range and reach higher distortion amplitudes. The moderate negative correlation of -0.60 calculated for this data (compare Figure 3.28) is most likely based on the different ranges in the two states *PV on* and *PV off*. In contrast, a power dependence during *PV on* is not visible. Figure A.12b shows an interharmonic distortion at 995 Hz close to 1000 Hz component in Figure A.12a. It lies within the band of correlation coefficients at -0.27 (compare Figure 3.28). As observed before, the interharmonic amplitudes have much smaller values compared to harmonics. Other than the smaller amplitudes, the right scatter plot shows the same characteristics as the left plot: The black points during operation of the PV system do not change behavior with power; only the red points during *PV off* show a broader distribution in comparison. Again, the moderate negative correlation likely only detects the differences between black (*PV on*) and red (*PV off*) states.

Beyond the moderate negative correlations around 1000 Hz discussed above, Figure 3.28 also shows strong correlation coefficients at single frequencies. For example, the lowest Pearson coefficient is -0.70 at 950 Hz. An interharmonic component only a few Hertz lower, at 945 Hz, has a negative correlation of -0.28 . The scatter plots for these two components are shown in Figure A.13. The left-hand scatter plot of the harmonic at 950 Hz shows a non-normal distribution of the distortion amplitudes. Furthermore, the identified correlation, again, appears to result only between the states *PV on* and *PV off* but no distinct power dependence is visible during operation (black points). The same holds for the interharmonic component in the right-hand plot but with a less complex distribution during *PV on*.

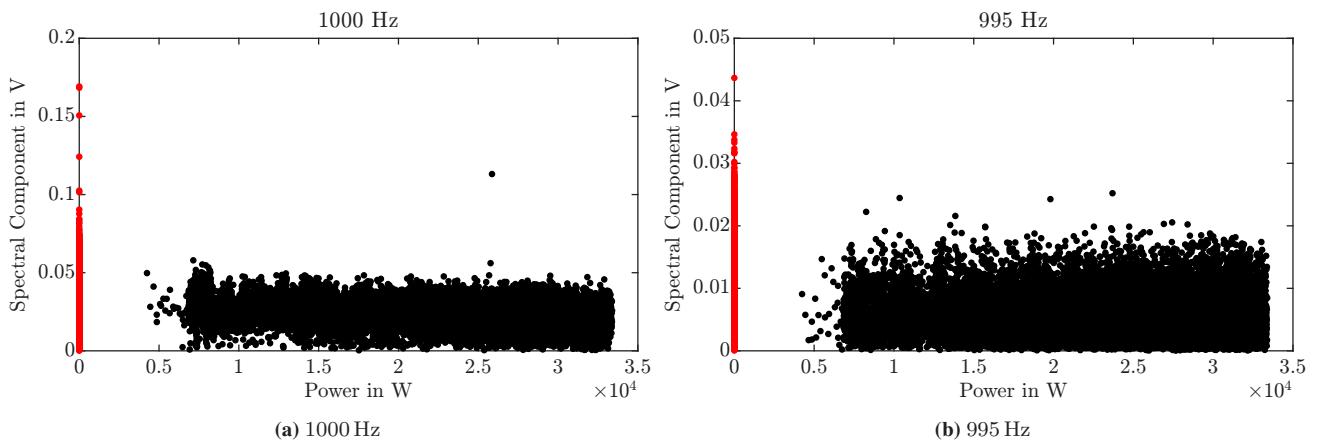


Figure A.12: Scatter plot between distortion amplitude time series at 1000 Hz and 995 Hz and the inverter power shows no power dependence of the amplitudes.

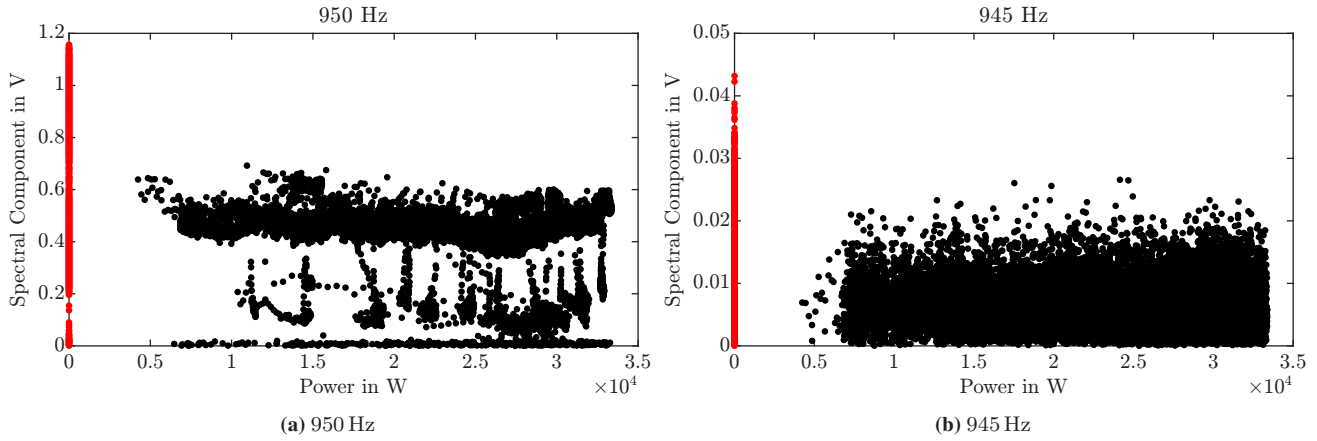


Figure A.13: Scatter plot between distortion amplitude time series at 950 Hz and 945 Hz and the inverter power shows no power dependence of the amplitudes.

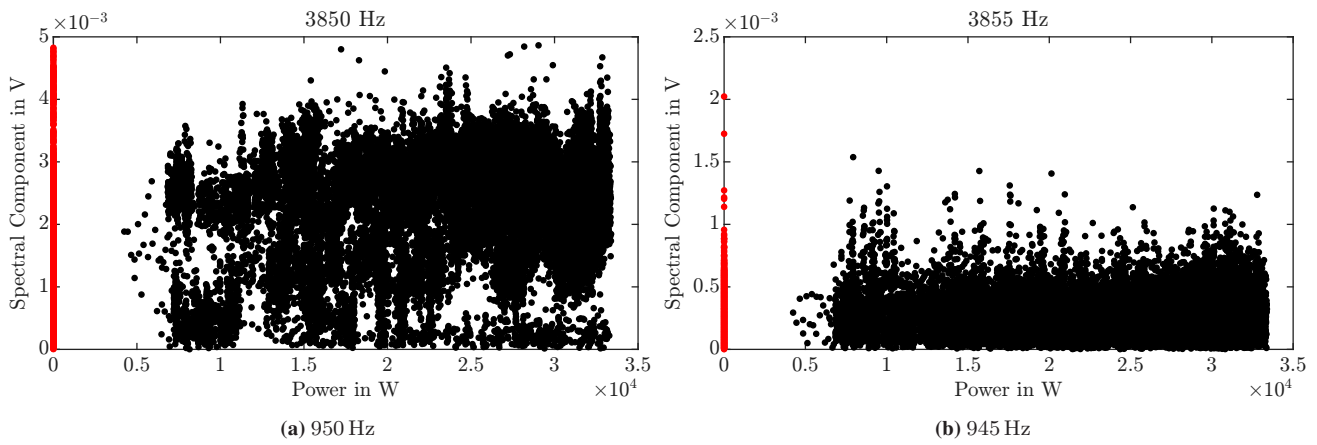


Figure A.14: Scatter plot between distortion amplitude time series at 950 Hz and 945 Hz and the inverter power shows no power dependence of the amplitudes.

Figure 3.28 shows the highest correlation coefficient of 0.57 at 3850 Hz. The respective scatter plot is shown in Figure A.14a on the left of Figure A.14. On the right in Figure A.14b, the scatter plot of a near interharmonic at 3855 Hz (correlation coefficient of 0.18) is shown in comparison. Again, both show non-normal distribution during the operation of the PV system. The difference between *PV on* and *PV off* is less pronounced here compared to the components evaluated in Figure A.12 and Figure A.13.

Overall, the correlation with the full power time series in Figure 3.28 reports a strong correlation of the distortion amplitudes with power at single frequencies. However, the scatter plots here reveal that the correlation analysis only detects the differences between the states *PV on* and *PV off* but not an actual power dependence during *PV on*.