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Framework to assess the stable operation of commercially available single-phase inverters for photovoltaic applications in public low voltage networks

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Abstract. This paper presents a framework to assess the grid compatibility of single-phase inverters connected to public low voltage network, which is characterized by a stable operation at reasonable emission. The assessment is based on considering emission, immunity and stability. The state of the art for commercially available devices relies only on the classical, impedance-based stability analysis based on the Nyquist criterion. However, experiences have shown that this is not sufficient for a statement towards the stable operation of an inverter, since the stable operation can also be affected by other factors than the network impedance, e.g. a background voltage distortion. Exemplary laboratory measurements of two commercially available single-phase PV inverters are presented to validate the statement by showing that despite the impedance-based stability criterion is met, inverters can still trip in presence of a high background voltage distortion. The paper concludes that the immunity of the inverter with regard to the voltage distortion at the point of connection (PoC) is additionally of importance for its stable operation.

Key words – Immunity, Inverters, Power Electronics, Power Quality, Stability.

0. Nomenclature

Symbol	Definition
x	Real value
$\underline{x}$	Complex value
$\hat{x}$	Amplitude value
$y(x)$	Dependency of y on x
X	Root mean square value / magnitude

1. Introduction

The demand to fulfil the climate goals leads to an increasing number of installed renewable energy generators in public energy networks [1]. These energy generators are of importance for the stable operation of the public energy supply, thus the stable operation of the individual power electronic (PE) devices (i.e. inverters) that connect the generator, e.g. a photovoltaic (PV) system, to the public low voltage (LV) network. Different approaches to analyse the stability of an individual device based on knowledge about the internal design, i.e. white-box approaches, and approaches that make use of the abstract input-output signal characteristics, i.e. black-box approaches that are typically based on laboratory measurements ([2], [3]), have been presented [4]. However, it has been documented in the field that besides compliance testing and white-box analysis, devices have shut down and not operated stable, e.g. [5]–[7].

The aim of this study is the presentation of a framework that addresses the stable operation from a broader perspective than the limitation to classical stability. The study relates to single-phase commercially available PV inverters in public LV networks. The proposed framework studies the impact of the LV network on the stable operation of the PV inverter but does not go into detail with regard to device-side impact factors, e.g. operating power [8] resulting from the solar panels etc.

The paper presents the state of the art in section 2 with regard to a brief overview of modelling approaches but also addresses the device behaviour in terms of emission, immunity and stability. Section 3 introduces the analysis of the stable operation related to the grid-side impact factors, i.e. the network impedance and the background voltage, and presents exemplary measurements of two commercially available single-phase PV inverters, both rated at 4.6 kW. Section 4 discusses the topic furthermore with regard to the component-based root cause and the inverter testing. Finally, section 5 concludes the study with a summary and relates to future work.

2. State of the Art

A. *System model*

The typical system model in frequency domain can be separated into the LV network and the coupled Norton model with regard to the small signal representation of

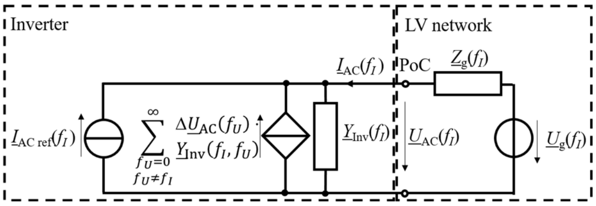

Figure 1: Model of an LV network and a coupled Norton model of a single-phase inverter.

commercially available, single-phase inverters and is depicted in Figure 1. In this study, the inverter is related to PV systems but called simply inverter in the following.

1) *LV network*

The LV network consists of a network impedance $\underline{Z}_{\mathrm{g}}$ and a background voltage $\underline{U}_{\mathrm{g}}$. The aggregated impedance characteristics reflect the linear voltage-current relations of the network equipment, e.g. transformers, cables, overhead lines, as well as all other grid-connected devices. The nonlinear voltage-current relations can be considered in the distortion of the background voltage $\underline{U}_{\mathrm{g}}$.

2) *Inverter*

The most advanced black-box representation for small signal studies is the coupled Norton model. It consists of a current source to represent the current response at a reference point “ref”. In addition, the small signal deviations from that reference point are reflected by the frequency coupling matrix (FCM) $\underline{\boldsymbol{Y}}_{\mathrm{Inv}}$. Currents at the same frequencies as the applied voltage frequencies in $\underline{U}_{\mathrm{PoC}}$ represent the diagonal elements of the FCM (classical admittance), while currents at different frequencies than the applied respective voltage frequencies represent the off-diagonal elements of the FCM (controlled current source). The FCM can be identified by applying a frequency sweep [9] over a single-frequent voltage distortion at the AC side of the inverter with regard to the reference point, which is also known as fingerprint when identifying PE devices in general [10]. By measuring the multi-frequent current response, the FCM can be calculated elementwise with

$$\underline{Y}_{\mathrm{Inv}}(f_I,f_U)=\frac{\underline{I}_{\mathrm{AC}\,i}(f_I)-\underline{I}_{\mathrm{AC\,ref}}(f_U)}{\underline{U}_{\mathrm{AC}\,i}(f_U)-\underline{U}_{\mathrm{AC\,ref}}(f_U)}. \qquad (1)$$

To specify the dependency on the amplitude and the phase angle of the voltage distortion, further variations can be considered over the amplitude and the phase angle though this factorizes the measurement duration. For devices that show a linear small signal characteristics with regard to the voltage distortion at the point of connection (PoC), e.g. single-phase inverters, a new measurement-based method has been proposed for a laboratory environment by making use of interharmonics [11] to reduce the measurement effort for the parametrisation. It is possible to derive the FCM analytically from available white-box models but this requires analytically sophisticated methods to describe all components mathematically to be considered in the derived FCM. In practice, not all components are typically included and described so that averaging and neglecting certain component characteristics is commonly applied. With regard to the frequency range, subharmonics and supraharmonics, e.g. [12], have also been studied though shutdowns related to supraharmonics are not known to the authors as of yet.

Further black-box approaches have been presented that make use of non-linear model structures, e.g. the Hammerstein-Wiener (HW) model [13], [14] and artificial neural networks (ANN) [15]. These models have been developed under the objective to study the harmonic frequency range. The neural network presents a model that enables time domain studies. Both, the HW and the ANN model, have not been studied for their feasibility for large signal analyses although the large signal characteristics of the voltage at the PoC have a main relevance for the stable operation.

B. *Emission, Immunity and Stability*

For a broader perspective on the stable operation, the emission, the immunity and the stability of any device, e.g. single-phase inverters, have to be studied.

1) *Emission*

The emission specifies how much current the individual devices injects, e.g. into the public LV network. The device emission for single-phase devices has to comply with respective standards, e.g. in Europe the *IEC 61000-3-2* and the *IEC 61000-3-12*. The tests are usually performed without any impedance between the test stand and the equipment under test (EUT). This implies a network impedance of zero. In the field, the disturbance levels caused by the emission of individual devices can exceed the immunity limits of the device itself and of other grid-connected devices. This can occur even if they comply with the standards by causing a too high voltage distortion due to the interaction with the network impedance, e.g. in case of pronounced resonances. Though this issue could be analysed and sorted out by the manufacturer, it requires knowledge about the individual LV network characteristics, where the device is installed.

2) *Immunity*

The immunity test levels (e.g. *IEC 61000-4-13*) specify the possible range of distortion at the PoC, for which an interference-free operation of the device is expected. With regard to the immunity test levels, the general procedure only tests for the specified immunity requirements, but cannot identify the individual device-specific limits, which are of interest for comparing the device performance with regard to the grid-robustness of individual device designs.

3) *Stability*

For electrical power systems, power system stability has been categorized into angle stability and voltage stability. Furthermore, small-signal and transient stability, mid-and long-term stability and large- and small-disturbance voltage stability have been introduced, e.g. [16]. Recently, the CIGRE Study Committee (SC) C4 and the IEEE Power System Dynamic Performance Committee have adapted the definition of power system stability further [17] into frequency stability, voltage stability, rotor angle stability, converter driven stability and resonance stability. The following work relates to the converter driven stability.

With regard to formal control theory, two main stability approaches are of importance for the state of the art with regard to single-phase inverters. One is related to the Lyapunov stability by making use of a white-box time-domain model, e.g. the switched model. Based on detailed knowledge about the inverter design, e.g. the software and hardware component topologies and the respective parameters, the Eigenvalues of the inverter can be calculated and the stability assessed. However, this is limited to manufacturers and study cases where the detailed knowledge about the inverter design is available. Typically, the design of a commercially available inverter is not disclosed. Therefore, a second approach has been developed that makes use of the previously introduced coupled Norton model that relates the input signals, e.g. the voltage at the PoC, to the output signals, e.g. the current at the PoC. This input-output relation can be represented in frequency domain by the inverter impedance characteristics and is used for the input-output stability that has been called the impedance-based stability analysis with regard to converter and inverter systems and applies the (generalized) Nyquist criterion [2]. The impedance-based stability analysis accounts however only for a particular operating point that depends on several impact factors, e.g. the impedance of single-phase inverters depends on the operating power that is based on the solar irradiance, which can be considered as quasi-stationary with regard to the harmonic frequency range. The quasi-stationary dependency implies that the change of the operating power is much slower than voltage changes in the harmonic frequency range so that the power is considered constant for a specific small signal analysis. However, the small signal analysis, which is also called steady state analysis, has to be performed for a suitable set of small signal models for a general statement.

With regard to the large signal stability analysis, e.g. the transient interaction with the LV network, the currently available analysis methods are white-box approaches, e.g. to analyse the impact of the synchronisation of the phase locked loop (PLL). For a suitable black-box large signal analysis, a structured framework that requires test signal specifications and test stand set ups is not known to the authors thus the large signal stability analysis represents one open issue for the black-box stability analysis.

As a general description of an instability, it can be stated that an increasing current emission in interaction with the LV network impedance can result in an increasing distortion of the voltage at the PoC. Eventually, the immunity limit of the device is exceeded, either due to a too high current or a too high voltage distortion. Consequently, rather the overall device immunity is of importance for the reliability instead of only the stability. Hence, besides instabilities related to classical stability the device immunity can be challenged in scenarios where the stability analyses would indicate a stable operation.

3. Impact factors

For a stable operation of the inverter, the voltage at the PoC is the dominant impact factor. Though most commercially available devices start operating at 5 – 10 % of their rated power, a too low power for the operation is not related to the reliability but rather the availability of the PV system with regard to the solar irradiance and not considered further as an immunity issue. Consequently, the analysis of the stable inverter operation is in the following related to the immunity of the device with regard to the impact factors from the network side, i.e. the network impedance and the background voltage, that determine the voltage at the PoC of the inverter. These two impact factors are separated into the steady state analysis and the transient analysis. The impact factors with regard to the following chapter are categorized in table I.

Table I. – Overview of impact factors

Category	**Impact factor**	**Signal characteristics**
A.1	Network impedance	Steady state
A.2		Transient
B.1	Background voltage	Steady state
B.2		Transient
C.1	Background voltage and network impedance	Steady state
C.2		Transient

A. *Network impedance*

1) Steady state

The impact of the network impedance in steady state can be related directly to the small signal stability analysis and represents a stability issue due to the violation of the principle of stability according to its classical definition. Specifically interesting for a reliable small signal stability analysis is the sensitivity on resonances of the LV network impedance [18], e.g. in the frequency range below 1 kHz [19] that can be included in practice by a probabilistic approach [20]. Approaches for black-box based laboratory small signal stability assessments for commercially available inverters have been presented in [21] and [3]. As an example, Figure 2 depicts the shutdown of a commercially available inverter, i.e. inverter I that has been measured in the laboratory for a sinusoidal background voltage at a highly inductive test stand impedance of 3.2 mH.

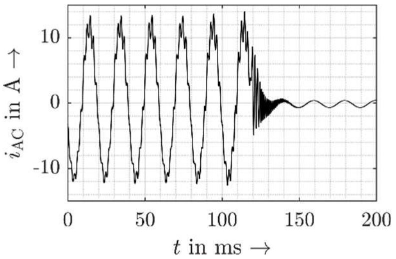

Figure 2: Shut down of inverter I for a test stand inductance of 3.2 mH at an operating power of 1.5 kW.

In the field, the steady state impact of an LV network impedance with a pronounced resonance due to the operation of a series voltage regulator has been the origin for the inverter shutdown documented in [7]. The phenomenon of this so-called harmonic stability has firstly been reported more generally in the Swiss railway grid [6].

2) Transient

While the previous section refers to the steady state impact of the network impedance, sudden significant changes in the network impedance can also cause a shutdown due to the transient reaction of the inverter on the changes in the network impedance seen at the PoC. In practice, this has been reported with regard to the inrush of a transformers in a public LV network in Australia [5]. The impedance change will lead to a voltage distortion at the PoC resulting from the current response, e.g. of the inverter, but the origin is the change of the network impedance and not the change of the background voltage (cf. B.2 in the later). Currently, impedance changes are not considered for the testing. Respective laboratory measurements require a suitable definition of the step changes and the definition of the frequency-dependent impedance characteristics, e.g. resonance frequency, resonance amplification and more general magnitude and phase angle characteristics of the test stand impedance.

B. Background voltage distortion

With regard to the previous section 3.A, the impact of the background voltage distortion will affect the voltage distortion at the PoC but does not necessarily have to cause an interaction in terms of a loop back. Instead, for stiff grids and emissions of other grid-connected devices that are independent from the voltage at the PoC, e.g. switching frequencies defined by the modulator of pulse-width modulated (PWM) PE devices, the background voltage can be unaffected by the current injection of the inverter at the PoC. With regard to classical stability analysis, the background voltage is not considered in the impedance-based stability criterion. It is treated as a disturbance that can excite the system. However, since it is expected that a stable system provides sufficient damping, a dynamic excitation is expected to decrease and a constant excitation is expected not to cause an increasing current response.

1) Steady state

In practice, a constant background voltage distortion can still cause too high currents and voltages at the PoC. The inverter can typically not start and fails to synchronize during the attempt to set the intended operating point according to the maximum power point tracker (MPPT). Some inverters have e.g. shown a much higher sensitivity on even order harmonics in the laboratory compared to the neighbouring odd order harmonics. While in public LV networks, even order harmonics have usually significantly lower magnitudes than the neighbouring odd order harmonics, this can be of interest for the device identification and testing methods.

2) Transient

Measurements of transient voltages [22] as well as a framework [23] to assess the transient inverter characteristics demonstrate the importance to also include the dynamics in the assessment of the stable operation of the inverter. As an example, the individual current responses on the same step change of the phase angle, i.e. 90° after 150 ms, at power frequency in the voltage at the PoC are presented in Figure 3 for two inverters, i.e. inverter I and inverter II at an operating power of 2.3 kW. Inverter II can handle this large phase angle variation while inverter I shuts down.

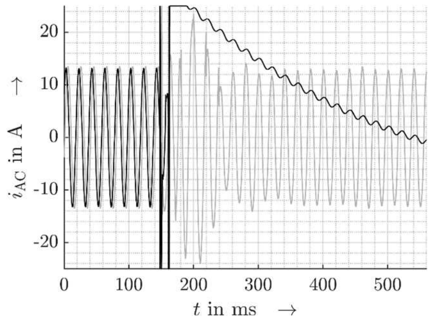

Figure 3: Current response of inverter I (black) and inverter II (grey) on a step change in the phase angle of the voltage at the PoC.

C. Combined impact of network impedance and background voltage

In the field, the background voltage distortion and the network impedance are both present. A distorted background voltage coming from a large number of installed inverters and the presence of the network impedance both together caused severe interactions of inverters in a distribution network in the Netherlands [24].

1) Steady state

An exemplary laboratory measurement of inverter I is depicted in Figure 4 for a highly inductive test stand impedance with an inductance value of 3.9 mH and a background voltage with a “flat-top” voltage waveform [25] that is typically present in public LV networks in western Europe, e.g. Germany. The inverter was not able to operate stable for the combination of the test stand inductance with the applied “flat-top” background voltage waveform for an operating power of 1 kW. However, a stable operation was possible for the same set up, also at an operating power of 1 kW, but with a sinusoidal background voltage. With regard to the formal stability analysis, the Nyquist criterion indicates a stable operation for the set up neglecting the background voltage. This difference clearly indicates the limits of the Nyquist criterion with regard to the assessment of the overall stable operation of the inverter.

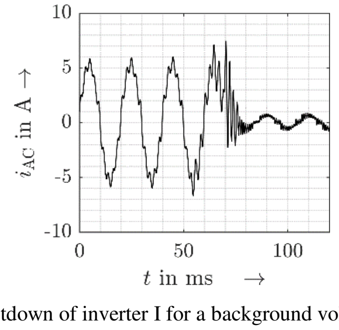

Figure 4: Shutdown of inverter I for a background voltage waveform with “flat-top” profile and a test stand impedance with an inductance of 3.9 mH at an operating power of 1 kW.

2) Transient

With regard to the previous sections, finally, also a superimposed change in the background voltage and the network impedance can occur at the same time. Generally speaking, though this is only the combination of A.2 and B.2, this is typically what happens in practice. It can be expected that changes in the network impedance will affect other grid-connected devices while a change in the background voltage distortion will eventually result from those devices with a nonlinear voltage-current characteristics.

4. Discussion

As mentioned previously, there are different approaches to analyse the stable operation of an inverter. Technically, it is possible to identify all types of instable operations by calculations and simulations in white-box studies if the required knowledge is available. Otherwise, measurement-based black-box approaches can be used for the small signal stability analysis, but not for all scenarios with regard to the impact factors as introduced in section 3 that cause instable operations. Independent from the available knowledge, it is not sufficient to study only selected scenarios.

A. Component-based root cause

While a detailed root cause analysis with regard to the implemented components is limited by the available knowledge of an individual inverter design, an abstract consideration of relevant components with impact on the inverter immunity is possible. Knowledge about the root cause of instable operations can be used to develop respective test signals to assess the limits of the stable operation of the inverter.

With regard to the control components, the PLL is one of the main components of relevance. The slope of the rate of change of the frequency, e.g. a step change in the phase angle, is of importance. The bandwidth determines the maximum possible rate of change Δt together with the maximum respective change of the angle $\Delta\varphi$ at which the PLL will fall out of synchronisation and until which rate of change it is able to resynchronize. A challenge for the PLL design is typically that a trade-off has to be accepted between a large bandwidth that enables a fast tracking of transients at the cost of a larger active phase angle characteristics in the resulting inverter impedance characteristics, which challenges the steady state inverter behaviour in terms of the classical impedance-based stability. In the past, grid-synchronisation based on zero-crossing detection has failed in case of double-zero crossing but modern PLL algorithms have solved this issue.

The DC-voltage controller and the AC-current controller can saturate for highly distorted voltages and also for too high voltage/current reference signals due to large transients at the PoC.

Anti-islanding (AI) detection can be challenged during voltage sags and voltage interruptions. This phenomenon is rather related to earlier installed inverters that however might remain installed for another decade.

With regard to the implemented hardware, the grid-side filter circuit can lead to high harmonic currents in interaction with the inverter control and the network impedance thus causing a resonance or even an instability issue.

The main hardware components that are relevant for the shutdown are the overcurrent protectors and the overvoltage protectors that are chosen based on the voltage and current ratings of the other hardware components. Voltage sags are of relevance for the overcurrent protection. Voltage swells can trigger the overvoltage protection. Knowledge about the implemented protection devices gives information about the maximum voltage and current limits of the inverter before shutting down that can differ from the data sheet of the inverter provided by the manufacturer.

B. Immunity testing

With regard to testing the immunity of the inverter, the previous sections have demonstrated the need for further, distorted test voltages as well as network impedances (with/without resonances). The test voltages should include realistic multi-frequent voltage distortions, as well as dynamic voltage changes, e.g. suitable step changes in the phase angle of the voltage, that are typically be found in public LV networks. A network impedance with a pronounced resonance should also be implemented in the test stand and the stable operation must be tested in combination with background voltage distortions.

5. Conclusion

This study presents the structured analysis of the immunity of single-phase commercially available PV inverters. The analysis and the respective measurements point out that the currently applied formal stability analysis for commercially available devices is not sufficient for a general statement towards the stable operation of the inverter. With regard to the small signal analysis in the harmonic frequency range, the simplification, e.g. to the impedance-based analysis, by neglecting the background voltage cannot be applied for a general statement on the stable operation in the harmonic frequency range as it only analyses the stability. The background voltage will not affect the device stability by classical definition but trigger shutdowns due to the device immunity limits. From a broader perspective, the different impact factors and the device reaction that can be related to the emission, immunity and stability of the device have to be considered. While it is possible to analyse the stable operation from a white-box perspective with detailed knowledge not only about the control but also the current and voltage ratings of the hardware and thus considering overcurrent and overvoltage protections, the available black-box methods do not consider overvoltages and overcurrents, e.g. as scenarios independent of the classical stability analysis. Consequently, it is rather appropriate to develop the measurement framework based on the impact factors in terms of steady state and transient characteristics of the voltage at the PoC and with regard to the network impedance.

One of the main outcomes of this study with regard to future work is the need for a measurement-based holistic framework to assess not only the stability but the overall stable operation of the inverter. For commercially available devices, this framework needs to provide a suitable measurement-based method that includes a representative set of voltage waveforms and test stand impedances, e.g. further large signal disturbances and dynamic changes, which affect the immunity of the inverter in a broader range. Besides the grid-side impact factors, also device-side impact factors can affect the stable operation of the inverter and have to be studied further in future.

Finally, when having developed a suitable measurement framework for inverters and gained the respective background knowledge for the relevant test signals, this measurement framework should also be adapted to further PE devices.

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References

[1] REN21, *Renewables 2022 Global status report*. Paris, 2022.

[2] J. Sun, "Impedance-based stability criterion for grid-connected inverters," *IEEE Transactions on Power Electronics*, vol. 26, no. 11. Institute of Electrical and Electronics Engineers (IEEE), pp. 3075–3078, Nov. 2011.

[3] E. Kaufhold, C. A. Duque, J. Meyer, and P. Schegner, "Measurement-Based Black-Box Harmonic Stability Assessment of Single-Phase Power Electronic Devices Based on Air Coils," *IEEE Transactions on Instrumentation and Measurement*, vol. 71. pp. 1–9, 2022.

[4] X. Wang and F. Blaabjerg, "Harmonic Stability in Power Electronic Based Power Systems: Concept, Modeling, and Analysis," *IEEE Transactions on Smart Grid*. Institute of Electrical and Electronics Engineers (IEEE), p. 1, 2018.

[5] M. Moghbel *et al.*, "Fluctuations in the Output Power of Photovoltaic Systems Distributed Across a Town with an Isolated Power System Using High-Resolution Data," in *2019 9th International Conference on Power and Energy Systems (ICPES)*, Dec. 2019, pp. 1–5.

[6] E. Möllerstedt and B. Bernhardsson, "Out of control because of harmonics-an analysis of the harmonic response of an inverter locomotive," *IEEE Control Systems*, vol. 20, no. 4. pp. 70–81, Aug. 2000.

[7] M. Höckel, A. Gut, M. Arnal, R. Schild, P. Steinmann, and S. Schori, "Measurement of voltage instabilities caused by inverters in weak grids," *CIRED - Open Access Proceedings Journal*, vol. 2017, no. 1. pp. 770–774, Oct. 2017.

[8] E. Kaufhold, S. Müller, J. Meyer, J. Myrzik, and P. Schegner, "Impact of DC power on the small signal characteristics of single-phase phtovoltaic inverters in frequency domain," 2023.

[9] N. M. Wereley and S. R. Hall, "Frequency response of linear time periodic systems," in *29th IEEE Conference on Decision and Control*, 1990, pp. 3650–3655 vol.6.

[10] S. Cobben, W. Kling, and J. Myrzik, "The Making and Purpose of Harmonic Fingerprints," *19th International Conference on Electricity Distribution*, no. 0764. pp. 21–24, 2007.

[11] E. Kaufhold, J. Meyer, and P. Schegner, "Fast measurement-based identification of small signal behaviour of commercial single-phase inverters," in *2021 IEEE 11th International Workshop on Applied Measurements for Power Systems (AMPS)*, Sep. 2021, pp. 1–6.

[12] E. Kaufhold, J. Meyer, and P. Schegner, "Impact of harmonic distortion on the supraharmonic emission of pulsewidth modulated single-phase power electronic devices," *Renewable Energy and Power Quality Journal*, vol. 19. pp. 577–582, Sep. 2021.

[13] N. Patcharaprakiti *et al.*, "Modeling of single phase inverter of photovoltaic system using Hammerstein–Wiener nonlinear system identification," *Current Applied Physics*, vol. 10, no. 3. Elsevier B.V., pp. S532–S536, May 2010.

[14] A. S. Abdelsamad, J. M. A. Myrzik, E. Kaufhold, J. Meyer, and P. Schegner, "Voltage-Source Converter Harmonic Characteristic Modeling Using Hammerstein-Wiener ApproachModélisation des caractéristiques harmoniques d'un convertisseur tension-source à l'aide de l'approche Hammerstein-Wiener," *IEEE Canadian Journal of Electrical and Computer Engineering*. pp. 1–9, 2021.

[15] E. Kaufhold, S. Grandl, J. Meyer, and P. Schegner, "Feasibility of Black-Box Time Domain Modeling of Single-Phase Photovoltaic Inverters Using Artificial Neural Networks," *Energies*, vol. 14, no. 8. p. 2118, Apr. 2021.

[16] P. Kundur, *Power System Stability and Control*. McGraw-Hill Education, 1994.

[17] N. Hatziargyriou *et al.*, "Definition and Classification of Power System Stability – Revisited & Extended," *IEEE Transactions on Power Systems*, vol. 36, no. 4. pp. 3271–3281, Jul. 2021.

[18] E. Kaufhold, J. Meyer, and P. Schegner, "Impact of grid impedance and their resonance on the stability of single-phase PV-inverters in low voltage grids," in *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)*, Jun. 2020, pp. 880–885.

[19] R. Stiegler, J. Meyer, S. Schori, M. Höckel, J. Drápela, and T. Hanzlík, "Survey of network impedance in the frequency range 2-9 kHZ in public low voltage networks in AT / CH / CZ / GE," in *25th International Conference on Electricity Distribution*, 2019, no. June, pp. 3–6.

[20] E. Kaufhold, J. Meyer, S. Muller, and P. Schegner, "Probabilistic Stability Analysis for Commercial Low Power Inverters Based on Measured Grid Impedances," in *2019 9th International Conference on Power and Energy Systems (ICPES)*, Dec. 2019, pp. 1–6.

[21] E. Kaufhold, J. Meyer, and P. Schegner, "Measurement-Based Black-Box Harmonic Stability Analysis of Commercial Single-Phase Inverters in Public Low-Voltage Networks," *Solar*, vol. 2, no. 1. pp. 64–80, Mar. 2022.

[22] E. Kaufhold, J. Meyer, and P. Schegner, "Transient response of single-phase photovoltaic inverters to step changes in supply voltage distortion," in *2020 19th International Conference on Harmonics and Quality of Power (ICHQP)*, Jul. 2020, pp. 1–6.

[23] E. Kaufhold, J. Meyer, and P. Schegner, "Measurement Framework for Analysis of Dynamic Behavior of Single-Phase Power Electronic Devices," *Renewable Energy and Power Quality Journal*, vol. 18. Granada, Spain, pp. 494–499, 2020.

[24] J. H. R. Enslin and P. J. M. Heskes, "Harmonic Interaction Between a Large Number of Distributed Power Inverters and the Distribution Network," *IEEE Transactions on Power Electronics*, vol. 19, no. 6. Institute of Electrical and Electronics Engineers (IEEE), pp. 1586–1593, Nov. 2004.

[25] R. Langella, A. Testa, J. Meyer, F. Moller, R. Stiegler, and S. Z. Djokic, "Experimental-Based Evaluation of PV Inverter Harmonic and Interharmonic Distortion Due to Different Operating Conditions," *IEEE Transactions on Instrumentation and Measurement*, vol. 65, no. 10. pp. 2221–2233, Oct. 2016.