Impedance-based power system stability analysis based on a power quality assessment toolbox – Advantages and challenges

***Bernd Weise* [1*], *Thomas Würl* [1]**

[1] *DIgSILENT GmbH, Heinrich-Hertz-Str. 9, 72810 Gomaringen, Germany*
* *b.weise@digsilent.de*

Keywords: POWER SYSTEM STABILITY, IMPEDANCE-BASED STABILITY ANALYSIS, SMALL SIGNAL STABILITY, FREQUENCY-DOMAIN MODELLING, FREQUENCY SWEEP

Abstract

Due to their fast control, inverter-based resources (IBR) can interact with the network impedance, other converters or rotating machines over a wider frequency range than synchronous generators. This increases the risk of resonances at sub- and super-synchronous frequencies. Impedance-based stability analysis is a suitable method for investigating the small-signal stability in the frequency domain. IBR dominated power systems require network analysis software tools for a system wide analysis. The paper focuses on the approach of using the frequency sweep function of a power system analysis software's power quality assessment toolbox in the frequency domain. Provided that suitable frequency-dependent impedance characteristics of IBRs and rotating generators are given (or can be derived), the frequency sweep function is capable of determining resonance frequencies and predicting whether a resonance is stable or unstable. The pros and cons of this approach and possible limitations are discussed. For a complete stability analysis, the frequency sweep function needs to be extended in order to determine stability margins by analysing the Nyquist curve and criterion for IBRs. Examples are given for the analysis of single IBR connections and multiple IBR connections to power systems. The advantages and challenges for practical application are discussed.

1 Introduction

Due to their fast controls, inverter-based resources (IBR, incl. HVDC VSC/MMC and STATCOM) can interact with the network impedance as well as with other converters or rotating machines in a wider frequency range, compared to conventional synchronous generators. This increases the risk of resonances which might be well damped, poorly damped or even unstable at sub-synchronous as well as super-synchronous frequencies. Observations of corresponding oscillations in power systems have been reported in recent years, e.g. [1, 2]. Several technical reports and guidelines related to the subject are published, which underlines the growing importance, e.g. [3, 4, 5]. The German roadmap for power system stability towards supply with 100% renewable generation addresses the topic as *resonance stability* [6, 7], which includes *resonance stability* and *converter-driven stability* as defined in [8], both in super-synchronous (harmonic) frequency range (often referred to as harmonic stability) as well as sub-synchronous frequency range.

The impedance-based stability analysis approach, e.g. [9 - 15], is a suitable method for investigating the small signal stability of grid connected IBRs in the frequency domain. For the investigation of larger IBR-dominated power systems, network analysis software tools are required for a system-wide analysis considering different relevant operating points, switching statuses of the network including planned outages or unplanned contingencies.

This paper focuses on the approach of using the frequency sweep function of a power system analysis software's power quality assessment toolbox in the frequency domain. In joint cooperation with a transmission system operator (TSO), DIgSILENT conducts a proof of concept, to demonstrate the usability of the Frequency Sweep function for impedance-based stability analysis, to identify advantages, challenges and possible limitations. The paper presents intermediate results of the proof of concept which is still in progress. The methodology is described in Chapter 2, including a discussion of its pros and cons. In Chapter 3, exemplary results are provided, which include IBRs as well as synchronous generators. The examples illustrate advantages and challenges for practical application, which are discussed in Chapter 4. Conclusions are drawn in Chapter 5.

2 Methodology

Power quality assessment for larger networks is typically done via harmonic load flow calculation to determine the harmonic voltages and currents and their propagation within the network (voltage and current components with integer and non-integer multiples of the fundamental frequency), supplemented by the frequency sweep calculation of the network (including generating units and loads) to identify resonance frequencies within the power system and to adapt harmonic filter layout. The frequency range of the frequency sweep calculation can cover the subharmonic and harmonic frequency range, i.e. sub-synchronous and super-synchronous frequencies, typically up to 10 kHz.

The original version of this paper was presented at the 23rd Wind & Solar Integration Workshop (Session 4C) and published in the workshop's proceedings.
Reprint version revised by authors after the 23rd Wind & Solar Integration Workshop; text revisions are marked in green.

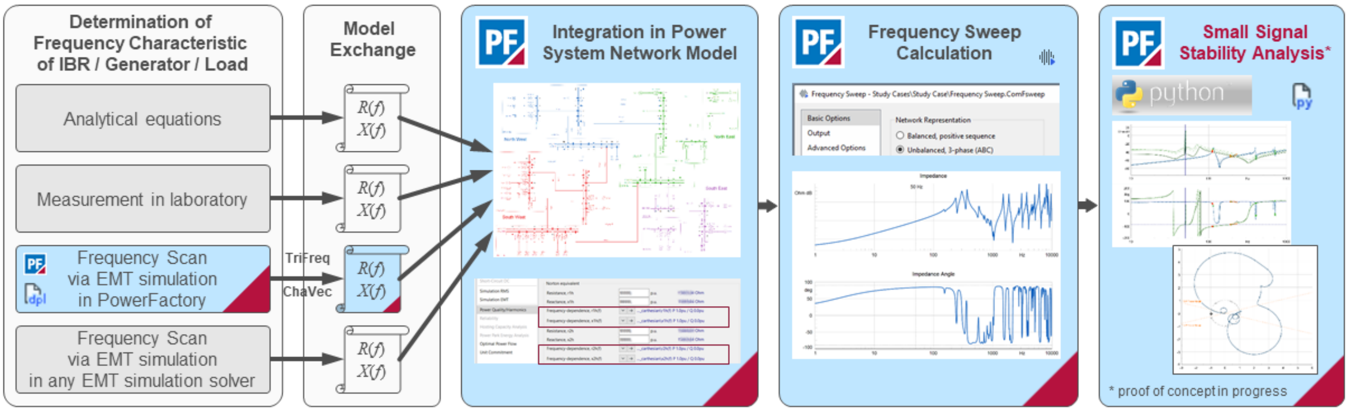

Fig. 1: Workflow for impedance-based stability analysis via Frequency Sweep function in *PowerFactory*

In the past, power electronic converters (mainly line commutated converters, LCC) were usually treated as ideal harmonic current sources for power quality assessment, representing an open circuit in the network model for frequency sweep calculation. With higher shares of voltage source converters (VSC), the modelling approach has changed in recent years. Nowadays, IBRs can be considered as frequency-dependent Norton or Thévenin equivalents, having frequency-dependent impedances represented in positive, negative and if applicable zero sequence, or in phases [16, 17]. The dependency of the equivalent's impedance on the operating point of the IBR (defined by active power P, reactive power Q and voltage magnitude U) will be included in the toolbox of the power system analysis software *PowerFactory* version 2025. With this modelling approach, *PowerFactory*'s Frequency Sweep function is well suited to be used for impedance-based stability analysis. Fig. 1 shows the workflow to perform the impedance-based stability analysis via frequency sweep function. The individual steps are explained in more detail in the following sections.

2.1 Determination of the frequency characteristic of an IBR / generator / load

The frequency characteristics of an IBR define its equivalent impedance, which is understood as a frequency-dependent small-signal impedance in this context. It is a complex quantity in sequence components or dq components. In the work presented in this paper, the representation in sequence components is used. The frequency characteristics of synchronous generators (SG) and loads (e.g. power electronic loads) can be described by their equivalent impedances in the same way.

The frequency-dependent equivalent impedance of an IBR (or SG, load) can be determined via

- measurements in laboratory (for example with differential impedance spectroscopy [18, 19]),
- frequency scan using EMT simulation with accordingly detailed time-domain models (in *PowerFactory* or any other EMT simulation solver), or
- in analytic form with equations describing the according transfer functions.

For the frequency scan with EMT simulation, a test system as depicted in Fig. 2 is used. In addition to the fundamental frequency voltage u_{f1} a small perturbation voltage u_{fp} with perturbation frequency f_p in the positive or negative sequence is applied (zero sequence only if applicable). The current response of the IBR is measured. The simulated time curves of voltages $u(t)$ and currents $i(t)$ are post-processed via fast Fourier transformation (FFT), or a similarly suitable method, to extract the frequency components with magnitude and angle. The complex impedance $\underline{Z}$ or admittance $\underline{Y}$ at perturbation frequency f_p is calculated based on the complex phasors of voltage $\underline{U}$ and current $\underline{I}$ at f_p. When using average EMT models, the calculation is as written in Eq. 1 and 2. In cases of switched EMT models, which have harmonic emissions themselves, more sophisticated calculations might be needed to exclude the pre-existing harmonic emissions. If the perturbation is in the positive sequence, the positive sequence impedance or admittance are determined; if the perturbation is in the negative sequence, the negative sequence quantities are derived. The procedure is repeated with all perturbation frequencies of interest in the desired frequency range.

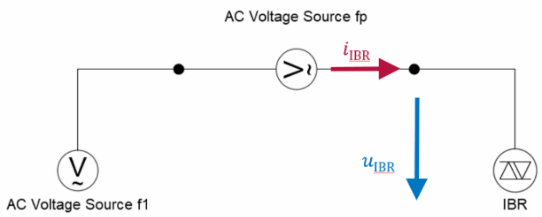

Fig. 2: Test system for frequency scan with EMT simulation

IBR impedance: $\underline{Z}_{IBR}(f_p) = \underline{U}_{IBR}(f_p)/\underline{I}_{IBR}(f_p)$ (1)

IBR admittance: $\underline{Y}_{IBR}(f_p) = \underline{I}_{IBR}(f_p)/\underline{U}_{IBR}(f_p)$ (2)

In addition to the self-impedance (or self-admittance), which is described by Eq. 1 and 2, the transfer impedance (or transfer admittance) can be derived, which describes the coupling of positive and negative sequence with a frequency shift of two times the fundamental frequency.

Fig. 3 shows an example of the positive and negative impedance of a VSC with grid-following control in dq-reference frame (PLL-based), reactive power control on the

The original version of this paper was presented at the 23rd Wind & Solar Integration Workshop (Session 4C) and published in the workshop's proceedings.
Reprint version revised by authors after the 23rd Wind & Solar Integration Workshop; text revisions are marked in green.

AC side, DC voltage control and a constant power source on the DC side. The figure depicts the results of the frequency scan for controller parametrisation with moderate gains (positive sequence in light blue, negative sequence in orange) and with very high gains (positive sequence in dark blue, negative sequence in red). The high gains cause the impedance to have negative real part over larger frequency ranges, which indicates negative damping.

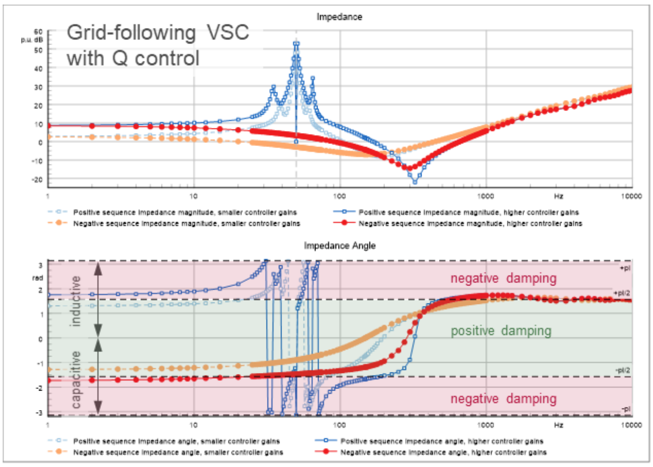

Fig. 3: Example of a VSC impedance in positive and negative sequence, derived via frequency scan (controller parametrisation with moderate gain in light blue and orange, and with high gain in dark blue and red)

2.2 Model exchange and integration in power system network model

For model exchange, just tables of the complex impedances or admittances as functions of the frequency have to be provided. The frequency domain models serve as black box models without any IT security risk. In contrast, EMT simulation models are either detailed open models, encrypted interpreted models or compiled models (DLL files).

The frequency-dependent impedances of IBRs, generators or loads in positive and negative sequence (and zero sequence if applicable) are used as input for the frequency-dependent network model in *PowerFactory* (parameter vector characteristic ChaVec with frequency scale TriFreq). With *PowerFactory* version 2025 the frequency-dependent impedance input can be grouped according to operating points (P, Q, U) to consider operating point dependencies.

2.3 Determination of the frequency-dependent impedance of the power system's network

The determination of the frequency-dependent impedance of the power system's network including connected installations (such as existing SGs, IBRs, and loads) is essential for impedance-based stability analysis. In general, the frequency-dependent impedance of the network can be determined either via frequency scan based on EMT simulation, or directly via frequency sweep function. Measurements of the network impedance at a given point of connection (POC) are only suitable at the low voltage or medium voltage level in real world. The synthesis of a frequency dependent network model of a (large) power system requires according network calculation or simulation software, which contains tools for handling large amounts of data.

The *frequency scan* method determines the impedance at a given node of a network via EMT simulation. The procedure is similar to the frequency scan of the IBR impedance (see Section 2.1). The time-domain network model has to be detailed enough to represent frequency-dependent effects sufficiently (e.g. skin effect, frequency-dependency of inductances $L(f)$, etc.).

The *Frequency Sweep* function uses a frequency-dependent model of the power system to calculate the resulting impedances directly in the frequency domain. It is numerically robust, comparably fast and easy to handle. Results can be obtained even if the power system model is not sufficient for EMT simulation or even load flow calculation.

Table 1 lists advantages and disadvantages of the two mentioned methods for determining the frequency-dependent impedances of the power system. Care has to be taken with respect to the terms *frequency scan* and *frequency sweep*. While they are well distinguished in this paper, the definitions used in literature are not always consistent. For example, in [4] the *frequency scan* is referred to as *frequency sweep*.

Results of the frequency sweep and of the impedance-based stability analysis are usually validated via comparison against EMT simulation results. However, this is not always reasonable, due to the different modelling possibilities in frequency and time domain (with limited representation of frequency-dependencies in time domain models, see Table 1).

The frequency sweep function is able to determine resonance frequencies and to predict whether a resonance is stable or unstable. A resonance point is indicated by a zero crossing of the imaginary part of the impedance, in conjunction with a dip of the impedance magnitude in case of a series resonance, and a peak of the impedance magnitude in case of a parallel resonance. A stable (damped) resonance is indicated by a positive real part of the impedance. An unstable (undamped) resonance is indicated by a negative real part of the impedance.

This is demonstrated by a simple parallel resonance circuit, which consists of an RL and an RC branch in parallel, see Fig. 4, Eq. 3 and 4. The RL branch in this example might be interpreted as a highly simplified network impedance, while the capacitive impedance might represent a connected device. The resistances define the damping. For demonstration purposes, the resistance of the RC branch is varied with frequency, artificially with negative or positive sign, in different frequency sweep runs. By reducing the resistance such that the total real part of the impedance becomes negative, the resonance turns from being stable to unstable. The resistance of this example is always positive at low frequencies, at fundamental frequency and at high frequencies, to ensure the system can be technically realised.

$$\underline{Z}_{\mathrm{RL}}(f) = R_{\mathrm{L}} + jX_{\mathrm{L}}(f) = R_{\mathrm{L}} + j2\pi f L \quad (3)$$

$$\underline{Z}_{\mathrm{RC}}(f) = R_{\mathrm{C}}(f) + jX_{\mathrm{C}}(f) = R_{\mathrm{C}}(f) - j\frac{1}{2\pi f C} \quad (4)$$

Fig. 5 depicts the results of the frequency sweep for the node in the middle of the circuit, which is the total impedance, Eq. 5.

The original version of this paper was presented at the 23rd Wind & Solar Integration Workshop (Session 4C) and published in the workshop's proceedings.
Reprint version revised by authors after the 23rd Wind & Solar Integration Workshop; text revisions are marked in green.

The blue curves indicate stable, the red/orange curves indicate unstable resonance. In case of a parallel oscillation circuit, the effective real part of the impedance at the resonance frequency gets larger with decreasing resistance. If the total resistance is zero, the real part of the impedance turns to infinite at oscillation frequency (theoretically). With further decreasing resistance, the real part of the impedance becomes negative and grows from negative infinity towards zero.

$$\underline{Z} = \underline{Z}_{\mathrm{RC}}(f)||\underline{Z}_{\mathrm{RL}}(f) = \frac{\underline{Z}_{\mathrm{RC}}(f)\cdot\underline{Z}_{\mathrm{RL}}(f)}{\underline{Z}_{\mathrm{RC}}(f)+\underline{Z}_{\mathrm{RL}}(f)} \qquad (5)$$

Table 1: Comparison of frequency sweep function versus EMT simulation for determination of the power system's frequency-dependent impedance

Aspect	**Frequency sweep calculation in frequency domain**	**Frequency scan via EMT simulation in time domain**
Numerical robustness	very good	can be challenging
Computational effort / simulation speed	small for pure positive sequence models, medium for unsymmetrical network representation	high
Frequency-dependent modelling of passive network components (lines, cables, transformers, reactors, etc.)	comparably easy to consider for all relevant elements (frequency characteristics, geometric line models)	high effort, requires parameter fitting (e.g. universal line model), usually not considered for all kinds of elements
Representation of active components (IBRs incl. controls, SG, etc.)	family of frequency dependent impedance characteristics (tabular format)	very detailed dynamic models required
Model exchange for active components (IBRs etc.)	simple tabular format, black box regarding control structure	open models or encrypted, compiled model, DLL exchange, IT security
Operating modes and parametrisation of controllers	requires individual frequency characteristics	full access to controller parameters
Operating points of IBR	requires individual frequency characteristics, then easily selectable	can be adjusted for each simulation run
Frequency coupling effects	so far not represented	included if accordingly detailed models are used
Sweep over operating points of network elements	simple to handle as long as according impedance characteristics are available	high effort (load flow convergence; potentially model ramp-up needed)
Network switching status; contingencies	to consider with low effort	high effort, as the frequency scan of the power system has to be repeated for each case
Multi connection assessment	possible without extra effort	requires additional frequency scan for additional connection points
Small signal analysis	yes	yes
Analysis of large-signal events	no	yes
Data handling	large amount of input data, especially impedance characteristics; tool assistance needed for data management	maybe smaller amount of data, but more complex model

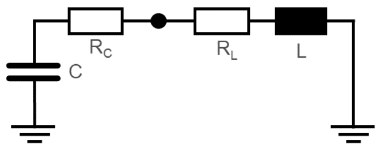

Fig. 4: Parallel resonance circuit example

While the frequency sweep function can identify whether a resonance is stable or unstable, it cannot determine any stability margin.

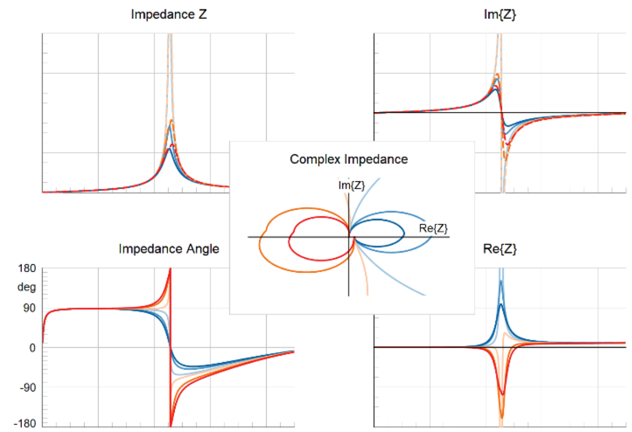

Fig. 5: Frequency sweep of a parallel resonance circuit with frequency-dependent resistance (blue: stable; red/orange: unstable)

2.4 Small signal stability analysis

For a complete stability analysis, the frequency sweep function (as well as impedance results obtained by frequency scan with EMT simulation) has to be extended in order to determine stability margins by analysing the loop gain of IBRs with the network through the Nyquist criterion. The Nyquist curve represents the complex closed loop gain function $\underline{L}(s)$. Within the aforementioned proof of concept, such extensions have been exemplarily realised by additionally implemented Python scripts for single-connection (an IBR connected to a power system, Eq. 6) and multi-connection assessment (several IBRs connected to a power system at different locations, Eq. 7). The analysis approach mainly follows [13, 14, 15]. With this, the stability analysis of a single IBR connected to an existing stable grid for grid connection compliance studies, as well as the analysis of a complete power system with multiple connected IBRs, generators and loads at once are possible.

Single-connection assessment:

$$\underline{L}(s) = \underline{Z}_{\mathrm{grid}}(s)/\underline{Z}_{\mathrm{IBR}}(s) \qquad (6)$$

Multiple-connection assessment:

$$\underline{L}(s) = \det\{[\mathrm{I}] + [\underline{Z}_{\mathrm{grid}}](s)[\underline{Y}_{\mathrm{IBR}}](s)\} \qquad (7)$$

Fig. 6 shows the Nyquist plot of the parallel resonance circuit example. At the intersection points of the impedance magnitudes of the RL and the RC branch (gain crossover, closed loop gain crossing the unit circle in the Nyquist plot), the phase deviation is smaller than 180° for cases with positive real part~~s~~ of the total impedance~~s~~ (stable cases, blue curves)

The original version of this paper was presented at the 23rd Wind & Solar Integration Workshop (Session 4C) and published in the workshop's proceedings.
Reprint version revised by authors after the 23rd Wind & Solar Integration Workshop; text revisions are marked in green.

and larger than 180° for the cases in which the real part of the impedance becomes negative (unstable cases of the example, red/orange curves). The closed loop gain function of the example (Eq. 8) encircles the -1 point for unstable cases, showing a phase crossover (crossing the negative real axis) beyond the -1 point. Phase and gain margins can be determined and allow the identification of clearly stable (uncritical, with large gain and phase margins), stable but critical (stable with small margins), or unstable cases. All shown stable cases of the example would be considered being critical, as they have a ~~smaller~~ phase margin smaller than 15°.

$$\underline{L}(f) = \underline{Z}_{\mathrm{RL}}(f)/\underline{Z}_{\mathrm{RC}}(f) \qquad (8)$$

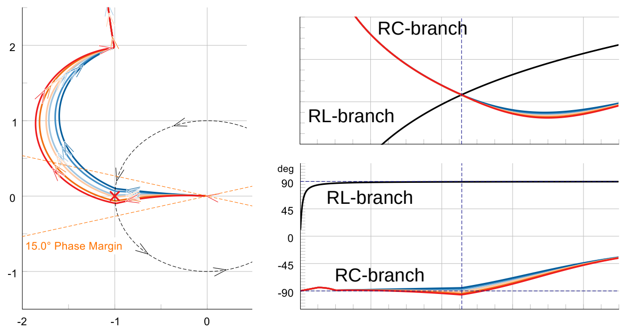

Fig. 6: Nyquist and Bode plot of a parallel resonance circuit example with frequency-dependent resistance

3 Exemplary Results

In this chapter, results of realistic examples are provided, which are discussed further in Chapter 4.

3.1 Small test system with two wind power plants

Fig. 7 depicts a simple example of a network containing two wind power plants (WPP) connected via transmission lines to an external grid (inspired by [15]). The WPPs are represented by aggregated VSC models with constant primary power sources (simple Type 4 wind turbine representation). Both WPPs have exactly the same rated power and grid-following controller design. Thus, their operating point dependent impedance characteristics (see Fig. 3) are identical. By applying the single connection assessment to WPP 1, the stability can be assessed via the Nyquist criterion.

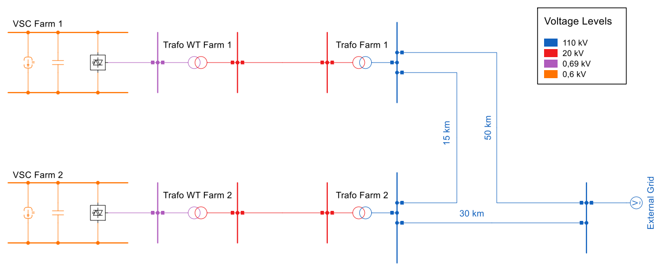

Fig. 7: Example with two wind power plants

While WPP 2 operates with P = 0.5 p.u. and Q = 0.0 p.u. in all cases, the operating point of WPP 1 is varied for the analysis. Fig. 8 – Fig. 11 show the results for the operating points of WPP 1 at P = 0.5 p.u. and Q = -0.1 p.u. (blue) / 0.0 p.u. (light orange) / 0.1 p.u. (dark orange). A resonance point is identified at approx. 77 Hz. The frequency sweep of the total impedance at the AC terminal of the VSC of WPP 1 shows the impact of the operating point on the stability (Fig. 8): while the system is stable in the operating scenario with overexcited reactive power injection (Q = 0.1 p.u., impedance angle within +/- 90°, blue curve), it is unstable in the other scenarios (impedance angle exceeds +/- 90°, orange and red curves).

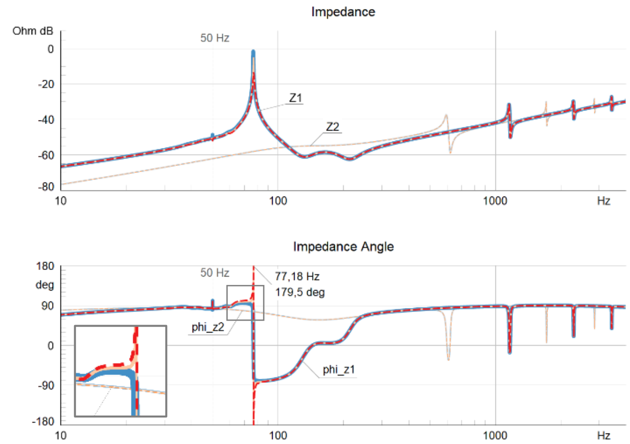

Fig. 8: Frequency sweep at VSC AC terminal of WPP 1; impedance magnitude and angle in positive and negative sequence; zoomed box shows detail at resonance point

The Nyquist and Bode plots of the stability analysis prove this result (Fig. 9 and Fig. 10). All three Nyquist curves show a phase crossover at around 77 Hz. For Q = -0.1 p.u., the curve does not encircle the -1 point. Q = 0 p.u. slightly encircles the -1 point. Further increasing the reactive power to 0.1 p.u. leads to the Nyquist curve fully encompassing the -1 point.

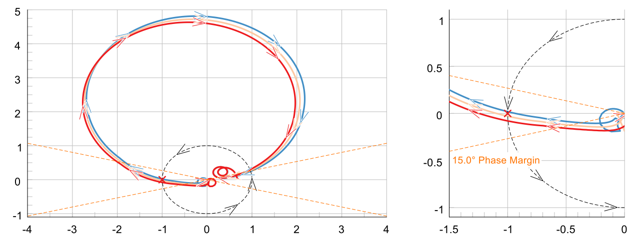

Fig. 9: Nyquist criterion for the wind power plants example for different reactive power operating points.

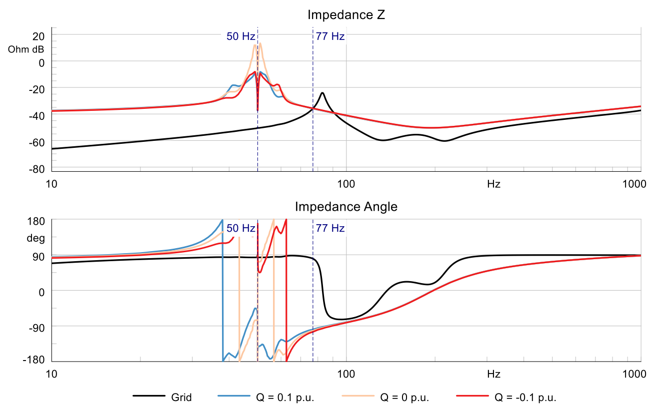

Fig. 10: Bode plot for the wind power plants example for different reactive power operating points.

The original version of this paper was presented at the 23rd Wind & Solar Integration Workshop (Session 4C) and published in the workshop's proceedings.
Reprint version revised by authors after the 23rd Wind & Solar Integration Workshop; text revisions are marked in green.

Fig. 11 shows the EMT simulation results of the space phasor current magnitude of the WPP 1 VSC for the different reactive power operating points. As the space phasor magnitude is constructed by the three phase currents oscillating at fundamental frequency (50 Hz in this example), the resonance is expected to be visible as the beat frequency, which is the difference of 77 Hz and 50 Hz equalling 27 Hz. The EMT simulation proves the expectation and validates the results obtained via impedance-based small signal analysis. The example emphasises the importance to consider all possible operating points and their impact.

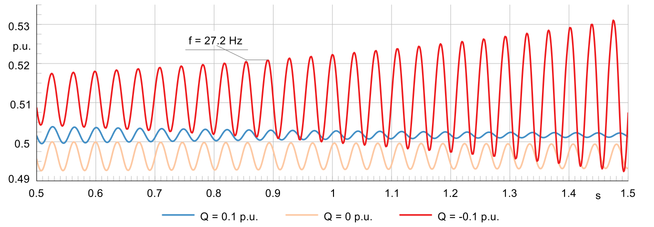

Fig. 11: EMT simulation results for the wind power plants example: space phasor magnitude of WPP 1 VSC current for different reactive power operating points

3.2 SSR example

The well-known IEEE First Benchmark Model for Computer Simulation of Subsynchronous Resonance (SSR) [20] is taken as example to test the frequency sweep and impedance-based stability analysis on a synchronous generator SSR problem. In this example, a series capacitor forms a series resonance circuit with the inductances of the power system including transformer and synchronous generator (SG), see Fig. 12. The electrical resonance frequency is approx. at 39.2 Hz [21]. Transferred to the multi-mass shaft of the mechanical turbine-generator-system with a frequency shift of one time the fundamental frequency (60 Hz), it is close to one of the torsional shaft modes (at approx. 20.21 Hz [20]), which causes an unstable oscillation. The implementation of the example in *PowerFactory* shows an unstable oscillation frequency in the electric quantities at 39.73 Hz (Prony analysis of the generator current time curve obtained by EMT simulation) [21].

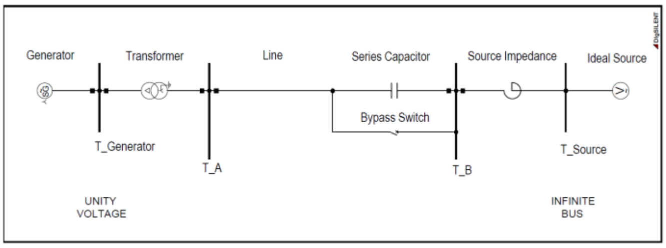

Fig. 12: Network diagram of the SSR benchmark example [21]

The frequency scan of the SG with dynamic multi-mass shaft model shows sharp spikes (thinner than 1 Hz) in the frequency-dependent impedance at the expected frequencies (corresponding to the torsional shaft modes), see Fig. 14. The frequency sweep shows the expected electric parallel resistance at the SG terminal (which is slightly moved in frequency due to the distribution of the inductances within the network, Fig. 13). Note, as seen from the generator terminal, the resonance is a parallel resonance with the capacitor on one side and the generator inductance on the other side.

The power system impedance at the SG terminal clearly shows the impact of the torsional shaft modes (Fig. 13). Very close to the electric resonance (approx. at 39.55 Hz), there is a negatively damped shaft mode, which is indicated by the negative real part of the impedance, or impedance angle exceeding +/-90° respectively (around 39.75…39.78 Hz, Fig. 13). Note, the generator model of the IEEE benchmark is not equipped with a voltage regulator (AVR) or power system stabilizer (PSS); therefore, the resulting impedance curves might differ in details from a real power plant. The example demonstrates that SSR can be represented and identified by frequency sweep calculation.

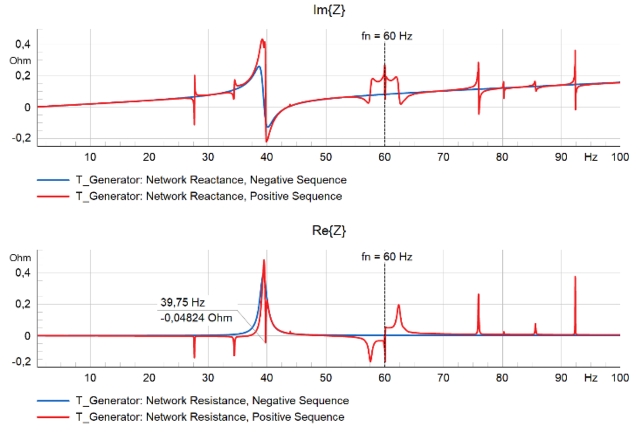

Fig. 13: Frequency Sweep result of the power system impedance at the SG terminal

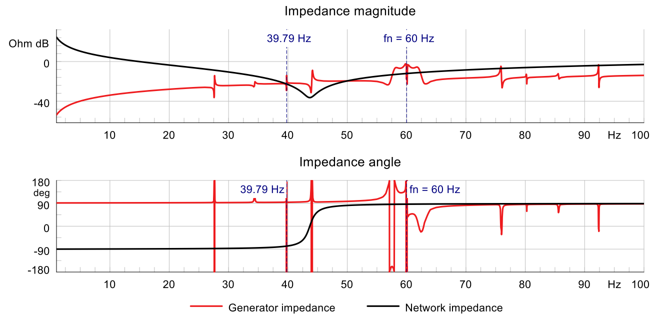

Fig. 14: Bode plots for the generator and network impedance

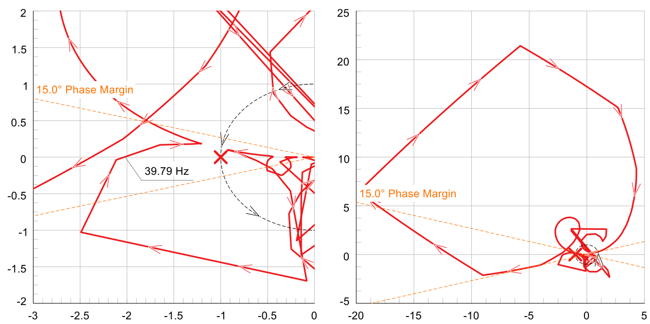

Fig. 15: Full Nyquist plot (right) and zoomed in section (left) at the SG terminal

Similarly, Fig. 14 and Fig. 15 indicate a resonance frequency identified through the Bode and Nyquist diagram at approx. 39.79 Hz. The example demonstrates the capability of the impedance-based stability analysis to identify unstable

The original version of this paper was presented at the 23rd Wind & Solar Integration Workshop (Session 4C) and published in the workshop's proceedings.
Reprint version revised by authors after the 23rd Wind & Solar Integration Workshop; text revisions are marked in green.

resonance of a synchronous generator caused by interaction of an electric resonance and a torsional shaft oscillation mode. The example further demonstrates the precision which is required to adequately reflect the shaft modes in the frequency-dependent impedance curve. A high resolution of the frequency is required around the shaft modes.

3.3 39 Bus New England System

The single-connection assessment allows to check if a grid connection or an operating point of a single machine is stable or has sufficient margins. However, it always requires a stable network (without right half plane poles) for the evaluation. If this is not granted, for example for future scenarios during network planning, a different option is necessary. The multi-connection assessment using the method described in [15] allows to check the stability of all converters against the grid.

To test this method, the literature example of the 39 Bus New England System [22, 23] is modified. On the basis of the EMT extension [23] available as a *PowerFactory* example [24], eight synchronous machines are replaced by VSCs, using EMT models and impedance characteristics according to their respective operating points. Fig. 16 shows the full Nyquist plot on the right and a zoomed in section on the origin. For this assessment, the analysis of the encirclements of the origin, (0,0)-point, are of interest in contrast to the single connection assessment, where the -1 point is relevant. The curve shows multiple encirclements of the origin, and therefore, indicates instability. This observation from the Nyquist curve can be verified by the EMT simulation results for the space phasor magnitude of the converter currents, shown in Fig. 17.

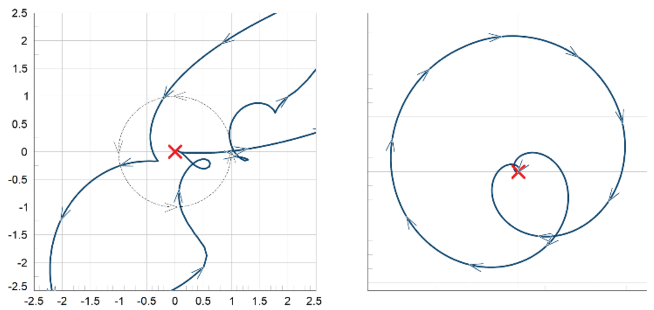

Fig. 16: Full Nyquist plot (right) and zoomed in section (left) from the multi-connection assessment of the 39 Bus New England System with added converters

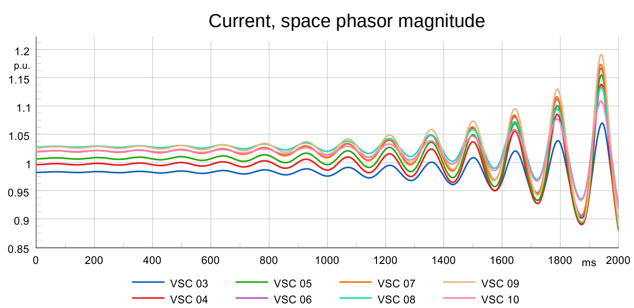

Fig. 17: EMT simulation of the modified 39 Bus System

4 Discussion and Outlook

The examples demonstrate that the frequency sweep function known from power quality assessment is well suitable as underlying calculation function for impedance-based stability analysis of power systems. In a simple assessment, the pure frequency sweep can indicate unstable cases, i.e. resonance points with negative real part of the total impedance, but it cannot compute any stability margins. The frequency sweep function can generate the input for proper impedance-based stability analysis of the Nyquist curve.

The simplified Nyquist criterion requires subsystems which are stable by themselves. This can be considered as being always true for already existing power systems and properly designed IBRs. Hence, for practical application, this limitation is not relevant. For academic research however, it has to be considered that the presented approach based on simplified Nyquist criterion may not be suitable for some artificially designed cases.

The ability of the approach to investigate the system stability even without converging load flow calculation enables the possibility to sweep through a lot of potential operation scenarios as an efficient screening method. This includes P and Q operating points, switching statuses, planned outages and unplanned network contingencies. More detailed scenarios can be obtained via load flow initialisation. Only those scenarios which are identified being critical or unstable may have to be analysed in more detail, e.g. through EMT simulations.

For stability analysis of a power system, it is crucial to be able to cover the whole frequency range of interest with sufficient resolution. The quality of input data is very important. All frequency dependent impedance curves, which are the input for the power system model, have to cover the whole required frequency range. A sufficient frequency resolution of the input curves and the frequency sweep itself is required to represent all aspects of interest (compare Section 3.2). In special cases, this may require internal knowledge from manufacturers.

The dependency of the operating point has to be considered as well, i.e. the whole range of operating points which are expected for application has to be reflected by the impedance curves of the IBRs (or SGs, loads). A family of equivalent impedances has to be exchanged and managed for power system models.

To ensure consistent quality of the frequency-dependent impedances, which are the main input data for the analysis, standardisation is required. According measurement procedure specifications have been drafted recently, for example Section 8.2.4 "Frequency dependent impedance measurement" in [25] or Section 5.2.5.2.3 in [26]. The exchange format should be standardised as well for efficient input in network models.

The effect of frequency coupling between positive and negative sequence via frequency shift can have an impact around and below fundamental frequency. The effect can be considered partially in single-connection assessment already, but still needs to be integrated in frequency sweep for complete consideration. The transfer impedance should be part of a standardised exchange format.

First experiences with the approach in larger network models are promising, especially taking the effectiveness of the multi-

The original version of this paper was presented at the 23rd Wind & Solar Integration Workshop (Session 4C) and published in the workshop's proceedings.
Reprint version revised by authors after the 23rd Wind & Solar Integration Workshop; text revisions are marked in green.

connection assessment approach into account (see Section 3.3). Investigations will be continued with real network data from the partnering TSO. The consideration of neighbouring networks (incl. under- and overlaid networks) requires further investigation. Also electronic loads should be included for consideration where relevant. For the aggregation of power parks, the impact of park controllers should be investigated, especially at sub-synchronous frequencies.

The extension of multi-connection assessment is planned for future investigation in order to identify which devices/ components or nodes/areas of a power system participate in oscillations.

Tests with grid-forming (GFM) converters have already been started. Related work including impedance scan results for examples of GFM virtual synchronous machine (VSM) implementations has been published [27].

5 Conclusion

The frequency sweep function known from power quality assessment is suitable as calculation method in the frequency domain to generate the input for impedance-based stability analysis. Single-connection assessment as well as multi-connection assessment for IBRs in a power system have been successfully demonstrated. Main advantages of the approach are good modelling capabilities in the frequency domain, simple model exchange, and a numerically robust and comparably fast, easy to use calculation method, which allows analysis of a larger number of operation scenarios and network contingencies within reasonable time. Even without proper stability analysis (Nyquist criterion), a pure frequency sweep calculation enables a simple stable/unstable indication. Main disadvantage is the inflexibility of the Thévenin or Norton equivalent of the frequency-dependent IBR model with regards to the operating point dependency and impact of controller parametrisation. This necessitates the exchange of a larger input dataset for the equivalent impedance. While the operating point dependency of the IBR equivalent impedance will be included in the data model of *PowerFactory* version 2025, consideration of the frequency coupling is still to be solved. Proving the method in larger network models is in progress. Special care will have to be taken related to the representation of neighbouring grids of interconnected power system as well as of over- or under-laid networks. The operating range and frequency range to be covered, the frequency resolution used for IBR models as well as the data format for model exchange should be standardized.

6 References

[1] C. Buchhagen, M. Greve, A. Menze, J. Jung: ‘Harmonic Stability – Practical Experience of a TSO’, 15th Wind Integration Workshop, Vienna, Austria, 2016

[2] Y. Cheng, L. Fan, J. Rose, et al.: ‘Real-World Subsynchronous Oscillation Events in Power Grids With High Penetration of Inverter-Based Resources’, IEEE Trans. Power Systems, Vol. 38, No. 1, Jan. 2023

[3] Cigré Technical Brochure 909, ‘Guidelines for Subsynchronous Oscillation Studies in Power Electronics Dominated Power Systems’, June 2023

[4] Cigré Technical Brochure 928, ‘Multi-frequency stability of converter-based modern power systems’, March 2024

[5] ESIG, ‘Diagnosis and Mitigation of Observed Oscillations in IBR-Dominated Power Systems – A Practical Guide’, Stability Task Force of the Energy Systems Integration Group (ESIG), Aug. 2024, https://www.esig.energy/wp-content/uploads/2024/08/ESIG-Oscillations-Guide-2024.pdf

[6] Bundesministerium für Wirtschaft und Klimaschutz (BMWK), ‘Roadmap Systemstabilität – Fahrplan zur Erreichung eines sicheren und robusten Betriebs des zukünftigen Stromversorgungssystems mit 100% erneuerbaren Energien’, Berlin, Germany, Nov. 2023, https://www.bmwk.de/Redaktion/DE/Dossier/roadmap-systemstabilitaet.html

[7] Themenpapier der Roadmap Systemstabilität, ‘AG3 – Resonanzstabilität, Winkelstabilität und Kurzschlussstrom’, Nov. 2023, https://www.bmwk.de/Redaktion/DE/Dossier/roadmap-systemstabilitaet.html

[8] IEEE PES TR77, ‘Stability definitions and characterization of dynamics behaviour in system s with high penetration of power electronic interfaced technologies’, April 2020

[9] J. Sun: ‘Impedance-Based Stability Criterion for Grid-Connected Inverters’, IEEE Trans. Power Electronics, Vol. 26, No. 11, Nov. 2011

[10] J. Sun: ‘Modeling and Analysis of Harmonic Resonance Involving Renewable Energy Sources’, IPST2013, Vancouver, Canada, July 2013

[11] M. Cespedes, J. Sun: ‘Impedance Modeling and Analysis of Grid-Connected Voltage-Source Converters’, IEEE Trans. Power Electronics, Vol. 29, No. 3, 2014

[12] I. Vieto, J. Sun: ‘Prediction of SSR in Type-III Wind Turbines Connected to Series Compensated Grids’, 14th Wind Integration Workshop, Brussels, Belgium, 2015

[13] J. Sun: ‘Two-Port Characterization and Transfer Immittances of AC-DC Converters—Part I: Modeling’, IEEE Open Journal of Power Electronics, vol. 2, pp. 440-462, 2021, doi: 10.1109/OJPEL.2021.3104502

[14] J. Sun: ‘Two-Port Characterization and Transfer Immittances of AC-DC Converters–Part II: Applications’, IEEE Open Journal of Power Electronics, vol. 2, pp. 483-510, 2021, doi: 10.1109/OJPEL.2021.3104496

[15] J. Sun, ‘Frequency-Domain Stability Criteria for Converter-Based Power Systems’, IEEE Open Journal of Power Electronics, vol. 3, pp. 222-254, 2022, doi: 10.1109/OJPEL.2022.3155568

[16] B. Weise, G. Lietz: ‘Parameterisation of Frequency Domain Models of Power Electronic Interfaced Renewable Energy Sources and VSC-HVDC for Harmonic Studies’, International Conference on Electrical Engineering (ICEE 2017), Weihai, China, July 2017

[17] IEC TR 61400-21-3: ‘Wind energy generation systems – Part 21-3: Measurement and assessment of electrical characteristics – Wind turbine harmonic model and its application’, Edition 1.0, 2019-09

[18] S. Rogalla, S. Kaiser, B. Burger, B. Engel: ‘Measured Impedance Characteristics of Solar Inverters up to 1 MW’, 10th Solar & Storage Integration Workshop, 2020

[19] S. Rogalla, S. Kaiser, B. Burger, B. Engel: ‘Determination of the Frequency Dependent Thévenin Equivalent of Inverters Using Differential Impedance Spectroscopy’, IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2020

[20] IEEE Subsynchronous Resonance Task Force of the Dynamic System Performance Working Group - Power System Engineering Committee: ‘First Benchmark Model for Computer Simulation of Subsynchronous Resonance’, IEEE PES Winter Meeting, 1977

[21] DIgSILENT: ‘Subsynchronous Resonance (SSR) Example’, *PowerFactory* application example & documentation

[22] M. A. Pai: ‘Energy Function Analysis for Power System Stability’, Kluwer Academic Publishers, Boston/Dordrecht/London, 1989, ISBN: 0-7923-9035-0, ISBN-13: 978-1-4612-8903-6

[23] Cigré Technical Brochure 736, ‘Power System Test Cases for EMT-Type Simulation Studies’, Working Group C4.503, August 2018

[24] DIgSILENT: ’39 Bus New England System’, *PowerFactory* application example & documentation

[25] IEC DTS 61400-21-4: ‘Wind energy generation systems – Part 21-4: Measurement and assessment of electrical characteristics – Wind turbine components and subsystems’, draft technical specification (88/1048/DTS), 2024-09

[26] VDE FNN Guideline Draft: ‘Technische Anforderungen an Netz-bildende Eigenschaften inklusive der Bereitstellung von Momentanreserve – Nachweis für Netzbildende Einheiten’, Version 0.1, July 2024

[27] B. Weise: ‘On the effect of inner control loops of grid-forming converters on the power quality of power systems’, 22nd Wind & Solar Integration Workshop, Copenhagen, Denmark, Sep. 2023

The original version of this paper was presented at the 23rd Wind & Solar Integration Workshop (Session 4C) and published in the workshop’s proceedings.
Reprint version revised by authors after the 23rd Wind & Solar Integration Workshop; text revisions are marked in green.