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C4 Power System Technical Performance**PS1 Power system stability aspects of decarbonisation of power systems and the road to net-zero****Frequency-Domain Screening Methods and Benchmarking for Converter-Based Systems**

Yicheng LIAO*
Energinet
Denmark
YLI
@energinet.dk

Özgür Can SAKINCI
TenneT
Netherlands
ozgurcan.sakinci
@tennet.eu

Daniel VAHLE
Amprion
Germany
Daniel.Vahle
@amprion.net

Niklas RIEMANN
50Hertz
Germany
Niklas.Riemann
@50hertz.com

Robert DIMITROVSKI
TenneT
Germany
robert.dimitrovski
@tennet.eu

Valentin COSTAN
RTE
France
valentin.costan
@rte-france.com

Nico KLÖTZL
TenneT
Germany
nico.kloetzel
@tennet.eu

Alexander NEUFELD
50Hertz
Germany
Alexander.Neufeld
@50hertz.com

Laurids DALL
Energinet
Denmark
LDL
@energinet.dk

SUMMARY

Frequency-domain screening is a valuable method for power system stability assessment, and it facilitates grid integration process and handling interoperability issues of power electronics-interfaced devices (PEIDs) due to its suitability for deriving equivalent representations from black-boxed control systems via frequency scan tests. However, the current applicable frequency scan tools are mostly developed based on local implementations by single tool developer and mainly applied for single device tests. There is lack of common understanding of the frequency scan methodology and testing experience of various tools, which makes it hard to extend frequency-domain screening for broader power system applications.

This paper aims for providing an overview of existing frequency scan methods and recommending practical testing guidance via benchmarking studies. Section 2 firstly summarizes the general process of frequency scanning and the commonly adopted implementation options in available tools. The user-important scan parameters include the perturbation configuration and perturbation parameters, the selected scan output formats, such as single-input single-output (SISO) and multi-input multi-output (MIMO) impedance models. Section 3 then follows by benchmarking various frequency scan tools implemented in two different electromagnetic transient simulation programs. The examples are selected on two

PEID systems, by scanning their impedance representations at the AC and DC points of connection, considering both SISO and MIMO models. The benchmarking studies reveal that various tool implementations can derive consistent frequency scan results, which provides confidence in using frequency scan results for further screening analysis. In addition, sensitivity analysis of tool implementation approaches and scan parameters is conducted, providing practical experience for users to assure qualified scan results. Based on the benchmarking experience, Section 4 further provides recommendations. A robust workflow for a single-device standalone frequency scan test is proposed to derive the minimum impedance profiles for a PEID's frequency-domain screening, capturing the necessary coupling, control and operating point dependence. Furthermore, a few useful features for the frequency scan tools are suggested. Section 5 finally concludes the paper with future applications of frequency screening methods and development needs from the transmission system operators (TSOs)' perspective.

KEYWORDS

Converter, frequency scan, frequency-dependent impedance, interoperability, model validation, small-signal analysis, stability screening

1 Introduction

1.1 Interoperability challenges

To meet Europe's Carbon-Neutral vision and ensure secure, efficient and resilient power systems, European TSOs collaborate to develop electricity systems that enable bulk renewable energy generation, stronger interconnections, and integration of flexible consumers. Modern grids increasingly rely on PEIDs from various vendors, whose dynamic interactions can cause adverse interoperability issues during commissioning or operation.

1.2 State of the art and gaps

To mitigate such risks, TSOs conduct studies to detect interoperability issues early, using inter alia time-domain simulations and frequency-domain small-signal analysis. Frequency-domain screening is an effective small-signal analysis method for de-risking interoperability issues of PEID systems during early project stages [1]. The applicability of such methods for identifying instabilities from sub-synchronous frequency range to beyond 1 kHz has been demonstrated extensively in literature [2]. Furthermore, performance specifications in the frequency domain can be made to quantify dynamic behaviour at a facility's connection point, which may simplify future grid integration process [3], [4].

Industry practices for frequency-domain screening require obtaining frequency-domain models, which can be derived using analytical and numerical approaches. Vendors can often use analytical methods to derive frequency-domain models during product design as they have full access to design details, while grid operators typically only receive black-boxed detailed models, making usage of analytical derivations impractical [5]. A benefit of frequency-domain screening is that the needed frequency-domain models can be obtained numerically from black-box models by perturbing voltages or currents at the point of connection (PoC) leading to an impedance-based frequency-domain model, a process known as frequency scan tests. These impedance-based models enable grid operators to conduct impedance-based stability assessment (IBSA) when integrating a facility into a larger grid [6].

For unified and reliable frequency-domain screening, impedance models must be compatible and sufficiently detailed. Existing open-source and in-house tools can perform frequency scan tests of EMT models [7]-[9], however are mostly used as local implementations to scan a single facility. Recent efforts have been done by benchmarking the effectiveness of using various frequency scan tools; however, the work primarily focuses on the consistent stability screening effects [10]. The lack of benchmarking across various implementations creates challenges for stability screening and compliance process of grid integration projects, as deviations between tools and methods remain unknown.

1.3 Contribution

This paper addresses the mentioned gaps by benchmarking existing EMT-based frequency scan methods and promoting a common understanding of procedures for consistent screening results. Section 2 reviews typical frequency scan methodologies for deriving impedance models. Section 3 presents benchmarking studies, and based on these Section 4 provides recommendations from TSOs' perspectives, including a robust frequency scan workflow and

key frequency scan tool features. Finally, Section 5 summarizes future applications of frequency-domain screening, remaining challenges and development needs.

2 Frequency Scan Methodology

This section provides an overview of the frequency scan methodology for deriving impedance profiles based on time-domain EMT simulations, which serves as the theoretical background for benchmarking studies.

2.1 General process

Frequency scan test is typically done in an electrical circuit simulation, by perturbing the system with small disturbances in either current or voltage at a PoC, measuring the respective other response, and then deriving the frequency-domain response as an impedance representation. The general process of frequency scan follows three steps:

- **Perturbation injection** usually implements a voltage or current perturbation source in the electrical circuit, to excite a system response. There are different ways to implement the perturbations, including various circuit configurations and perturbation parameters. The commonly adopted methods are briefly summarized in Section 2.2 and Section 2.3.
- **Time-domain analysis** is then carried out by simulating the electrical system to get the time-domain response, typically using an EMT tool. Depending on the targeted impedance reference frame, one can apply further coordinate transformations to the voltage and current responses.
- **Frequency-domain analysis** is finally applied to process the time-domain data, usually via the Discrete Fourier Transformation (DFT). This allows for obtaining the voltage and current responses in frequency domain and calculating the impedance at the PoC. The output impedance formats depends on the PoC definition and the reference frame definition, which can either be a single-input single-output (SISO) or a multi-input multi-output (MIMO) model, and will be introduced further in Section 2.4.

2.2 Circuit configuration of perturbation injection

The perturbation source is typically inserted at the PoC between a device under test (DUT) and a network (NET). There are four typical ways of implementing the circuit configuration for perturbation injection, as shown in Figure 1. The figure is illustrated based on AC systems, but the same principle applies for DC systems.

Commonly adopted methods are (a) series voltage source perturbation and (b) shunt current source perturbation, which inject perturbations only at perturbed frequencies in the frequency range of interest without altering the original system steady-state configuration. These require the original system to be small-signal stable. Choice of perturbation type and amplitude usually relies on the impedance values of the DUT and NET such that it ensures measurable responses without violating small-signal conditions.

Alternatively, method (c) decoupled source perturbation uses two independent sources at the PoC, enabling pure DUT or NET response and working even if the original system is unstable. Using decoupled sources should include not only the perturbation source but also the steady state source at the fundamental frequency, thus it requires identifying steady state operating

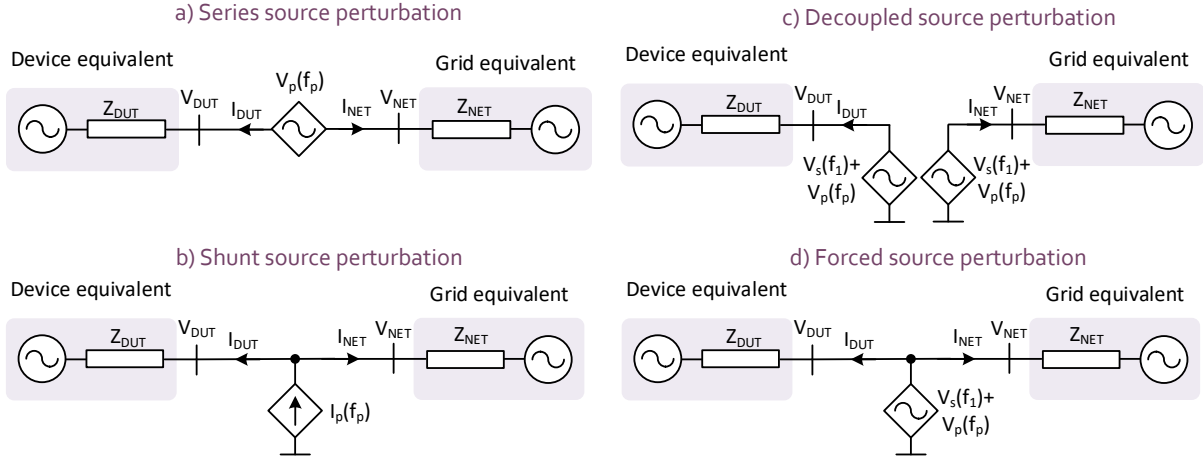


Figure 1 - Typical ways of circuit configuration for perturbation injection

point for parametrization. However, it may conflict with DUT voltage control modes if enabled as it adds stiff voltage sources at the PoC. Therefore, the decoupled source can also be implemented using current sources to achieve the same load flow to avoid this conflict.

Method (d) forced source perturbation simplifies (c) by using a single voltage source at the PoC, but loses flexibility in setting different perturbation parameters for each side.

2.3 Perturbation parameters

Besides the circuit configuration, perturbation parameter settings are crucial, as improper settings can distort frequency scan results. The perturbations should be designed to ensure that the system is excited with small disturbances but still operated within a small-signal condition and does not enter nonlinear operation. Therefore, key perturbation parameters are summarized here and their parameterization benchmarked in studies are described in Section 3.

- Single-tone or multi-tone perturbation type

The fundamental frequency scan technique relies on sinusoidal perturbation at one perturbed frequency each time, known as single-tone perturbation. Then the scan is iterated at different perturbed frequencies. This is easy for DFT analysis but requires more time for performing the scan.

Advanced methods have been developed to accelerate the scan process by injecting multiple sinusoidal perturbations of different frequency each time, known as multi-tone perturbation. Injecting more perturbed frequencies can accumulate the perturbation size, which may more easily go beyond the small-signal condition where the frequency scan is valid. Therefore, careful parameterization of the perturbation size is needed when applying the multi-tone perturbation.

- Perturbation duration

When the frequency scan is performed at different perturbed frequencies, the perturbation duration is important for obtaining correct scan results. It must be at least sufficient to ensure accurate DFT computation at each perturbed frequency. The minimal perturbation duration is recommended to be at least 3-5 cycles of the greatest common divisor of dominant existing frequency components based on the perturbed frequency. While some tools employ fixed durations based on user input, others implement varied or adaptive perturbation duration schemes to optimize scan efficiency.

- Perturbation size
Perturbation size must excite measurable responses without breaching small-signal assumptions. Given the frequency-dependent impedances of DUT and NET, fixed magnitudes may be inadequate, requiring iterative or adaptive adjustment across frequency ranges.

2.4 Output impedance formats in AC and DC scans

Depending on the defined PoC or impedance reference frames, the frequency scan can be derived in different output impedance formats. The commonly considered impedance formats by available tools for AC and DC scans are summarized in Table 1. It is found that various frequency scan tools generally apply the same workflow to calculate different impedance models, which is summarized in Figure 2.

3 Benchmarking Studies

3.1 Benchmarking method and tool overview

The benchmarking studies focus on six frequency scan tools, including open-source, commercial and TSO in-house tools, implemented in two EMT tools. The scanned impedance results are compared among different tools if the scan feature is available, and compared with the analytical models if the analytical models are available.

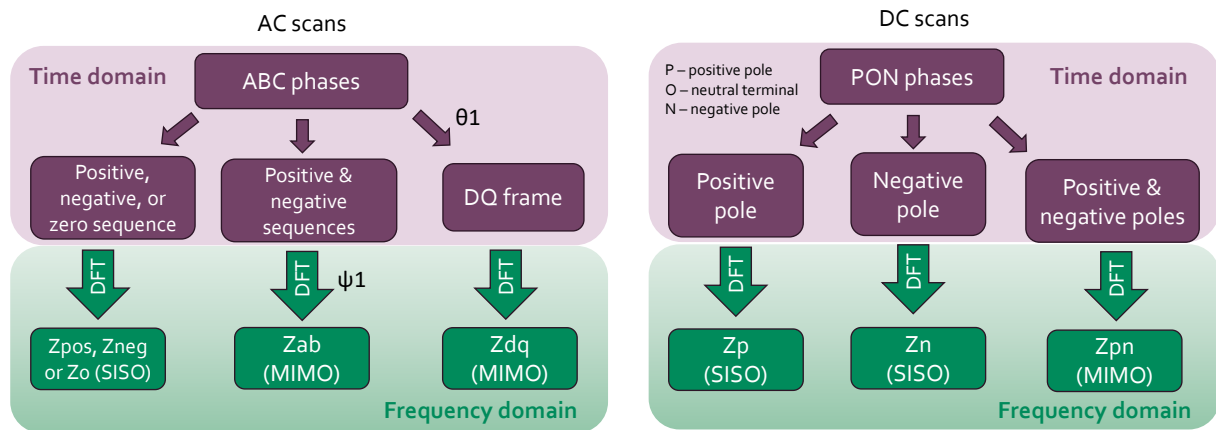


Figure 2 - General workflow for calculating AC and DC impedances

Table 1 - Output impedance formats for AC and DC scans

PoC	Impedance	Symbol
AC	SISO impedance model in positive, negative or zero sequence frames [2]	Zpos, Zneg, or Z0
	MIMO impedance model in $\alpha\beta$ reference frame [11]	Zab
	MIMO impedance model in dq reference frame [12]	Zdq
DC	SISO impedance model in monopole reference frame (between positive or negative pole to neutral)	Zp, Zn
	MIMO impedance model in bi-pole reference frame (neutral is defined as reference point)	Zpn

Table 2 - Overview of six frequency scan tools used for benchmarking

Tool name	EMT tool	Circuit configuration	Perturbation type	Perturbation size	Available scans
A	X	d)	Single or multi-tone	Fixed	AC MIMO, Zdq DC SISO
B	X	a) or b)	Single or multi-tone	Fixed	AC SISO AC MIMO, Zab AC MIMO, Zdq
C	X	a)	Single tone	Fixed Adaptive	AC SISO AC MIMO, Zdq
D	X	a) or b)	Single tone	Fixed	AC SISO AC MIMO, Zab AC MIMO, Zdq DC SISO DC MIMO
E	X	c)	Single tone	Fixed	AC SISO AC MIMO, Zab DC SISO
F	Y	a) or b)	Single tone	Fixed	AC SISO

Since different frequency scan tools do not have identical scan features, [Table 2](#) provides an overview of the available features from each tool. The following benchmarking cases only compare the tools if they have common features available.

3.2 Benchmarking systems and cases

The benchmarking considers AC and DC scans on two generic models:

- A generic two-level VSC based on averaged modelling with PQ control, phase-locked loop and current control. This model is implemented in both EMT tools X and Y and comes with an analytical model, and only AC PoC scan is performed
- A generic MMC-HVDC system, where both AC and DC PoCs are scanned. For AC PoC scans, both strong and weak grid configurations are considered, with the HVDC adopting either fixed Q control or Vac control. For DC PoC, the HVDC converter has either Vdc control or Pdc control. This system is only available in EMT tool X.

An overview of the benchmarking testing cases is summarized in [Table 3](#) in two benchmarking categories. The unified scans mean that all the tools' scans apply a unified scan setting, in order to verify the scan methods and consistent results. The sensitivity scans present cases where deviations are found in the scan results from different tools, indicating what are sensitive scan settings or parameters that affect the scan results.

3.3 Benchmarking results

3.3.1 Unified scans

U1. VSC AC scan

U1 case scans the two-level VSC's AC impedance Z_{pos} and verifies its analytical relationship with Zab, Zdq and grid impedance coupling. This test also benchmarks the scan tools in

Table 3 - Overview of benchmarking cases

Benchmarking category	Study cases	Scanned impedances	Purposes
Unified scans	U1. VSC AC scan	Zpos	Verify AC SISO scan methods with analytical models
	U2. HVDC AC scan	Zab, Zdq	Verify AC MIMO scan methods and consistency
	U3. HVDC DC scan	Zp, Zpn	Verify DC scan methods and consistency
Sensitivity scans	S1. HVDC AC scan under different control modes and grid conditions	Zdq	Identify impact of circuit configuration and control mode
	S2. HVDC AC scan using different perturbation types and sizes	Zab	Identify impact of perturbation types and sizes

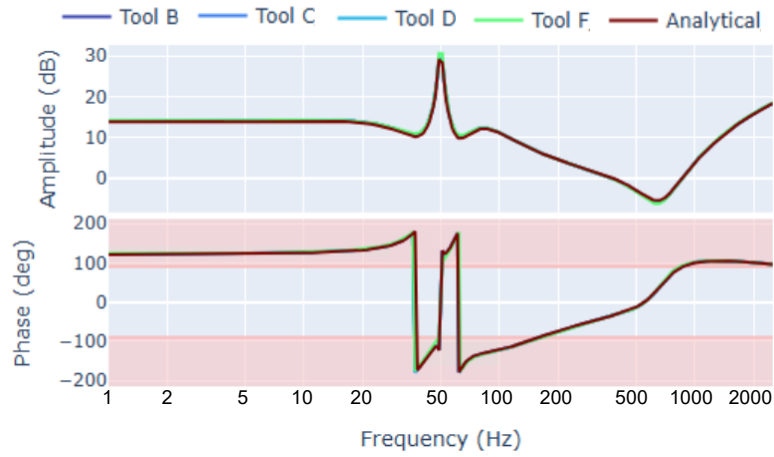


Figure 3 - Zpos SISO scan results of VSC compared with analytical models

different EMT tools.

Zpos scan is a SISO scan, which measures a closed-loop impedance response when coupling the DUT impedance and the NET impedance. Therefore, to reflect this coupling effect, Zpos scan results need to be benchmarked with the analytical model derived based on analytical modelling of Zab for both DUT and NET, using Equation (1)

$$Z_{DUT,pos}(s) = Z_{DUT,ab11}(s) - \frac{(Z_{DUT,ab12}(s) + Z_{NET,ab12}(s))(Z_{DUT,ab21}(s) + Z_{NET,ab21}(s))}{Z_{DUT,ab22}(s) + Z_{NET,ab22}(s)} \quad (1)$$

Figure 3 shows the scanned Zpos results compared with the analytical model, where all the tools' scan results are overlapped. This confirms the frequency scan tool equivalence between different EMT tools. The scan results agree with the analytical model, which verifies that the Zpos scan is dependent on the grid condition, as the coupling effects between the DUT and NET impedance according to (1) should be considered.

U2. HVDC AC scan

U2 case conducts MIMO impedance scans at the AC PoC of the HVDC system, where Zab and Zdq are scanned for both the DUT side and NET side. In this test, HVDC is operated in a strong

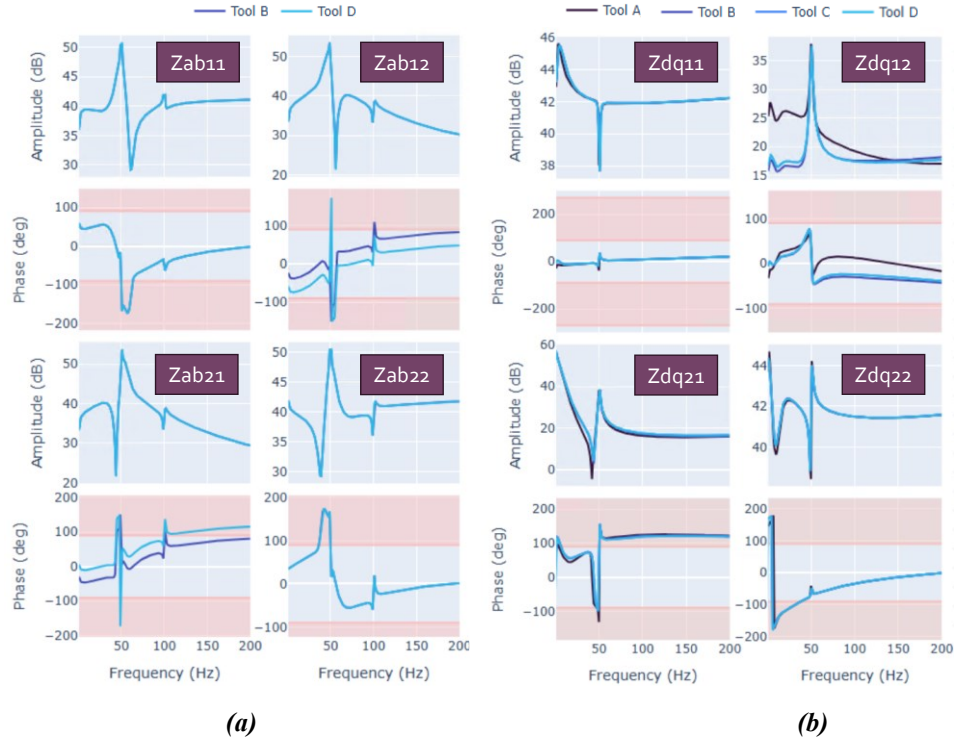


Figure 4 - AC impedance scan for HVDC in strong grid and Vac control (a) Zab; (b) Zdq

grid with Vac control. **Figure 4** shows the Zab and Zdq scan results for the HVDC.

- For Zab scan, Tools B and D almost obtain the same impedance scan results, except the off-diagonal elements with an opposite phase difference. This is caused by phase dependence behaviour in the Zab impedance representation, as different initial phase angles may be chosen by the tools based on different selection of time windows [11]. To use the scanned impedance for further stability screening, a phase compensation based on load flow angles may be needed.
- For Zdq scan, most tools have the same impedance scan results except Tool A, which uses the d) forced source perturbation for frequency scan. This comparison confirms that other tools using a) series source perturbation or b) shunt source perturbation can derive the same scan results. The deviation from Tool A in Zdq scan will be further analysed in S1 in Section 3.3.2.

U3. HVDC DC scan

U3 case scans the DC impedance of HVDC, and the results are shown in **Figure 5**. Tools A and D's SISO scans of positive-pole impedance Z_p are consistent in **Figure 5** (a), which are also consistent with the diagonal elements of the MIMO scan in **Figure 5** (b). The off-diagonal elements in the MIMO scan results in **Figure 5** (b) are much smaller than diagonal elements. These facts indicate that the tools can correctly identify the pole impedance, and in this HVDC system, the coupling between positive- and negative-pole impedances is very weak.

3.3.2 Sensitivity scans

S1. HVDC AC scan under different control modes and grid conditions

In addition to **Figure 4**, S1 case investigates more scans for the HVDC under different control

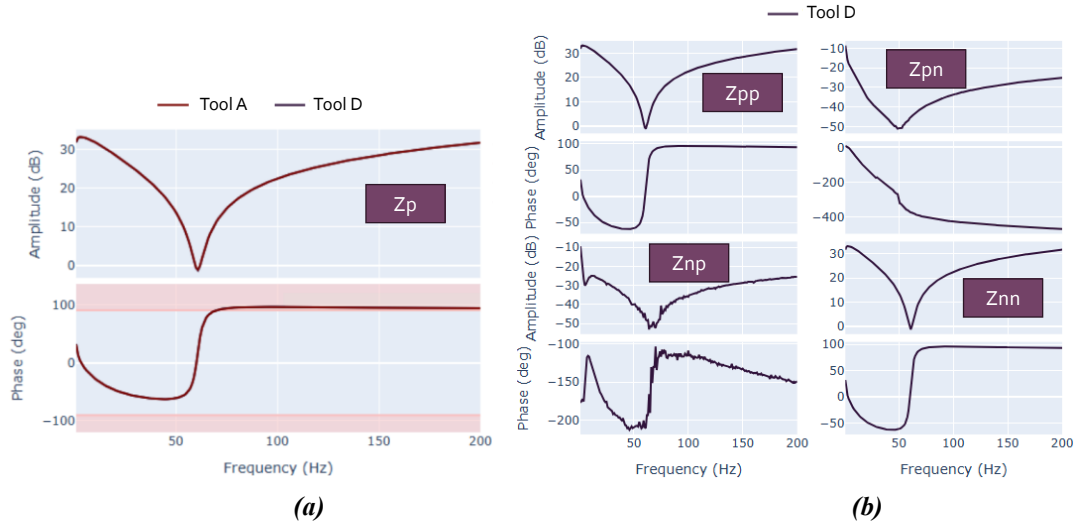


Figure 5 - DC impedance scan of HVDC. (a) SISO scan of Z_p ; (b) MIMO scan.

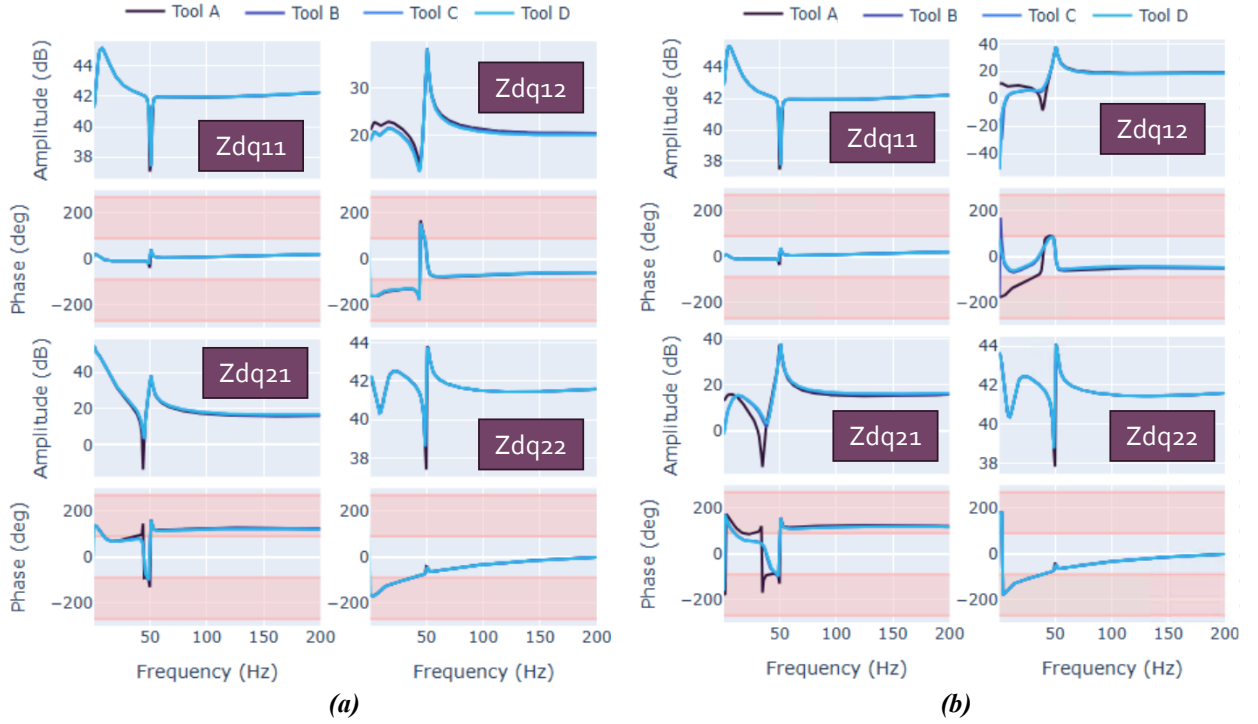


Figure 6 - Zdq scan for HVDC in two more scenarios (a) Weak grid, Vac control; (b) Strong grid, Q control modes and grid conditions, as shown in Figure 6, for two purposes:

- Reveal the tool implementation sensitivity
As Figure 4 reveals some deviations in the Zdq scan for the HVDC, more Zdq scans for the HVDC scan in two more scenarios are performed. Comparing Figure 6 and Figure 4 (b), it can be found that Tool A predicts Zdq differently compared with the other tools, and the other tools always obtain consistent results in every scenario. Tool A results in the smallest deviation in Figure 6 (a), which is the weak grid condition. In the other two scenarios, e.g. Figure 4 (b) and Figure 6 (b), the strong grids are applied, and the Zdq scan from Tool A has larger deviations in off-diagonal elements. These tests confirm that the Tool A using forced source perturbation is sensitive to the grid scenarios and control modes.

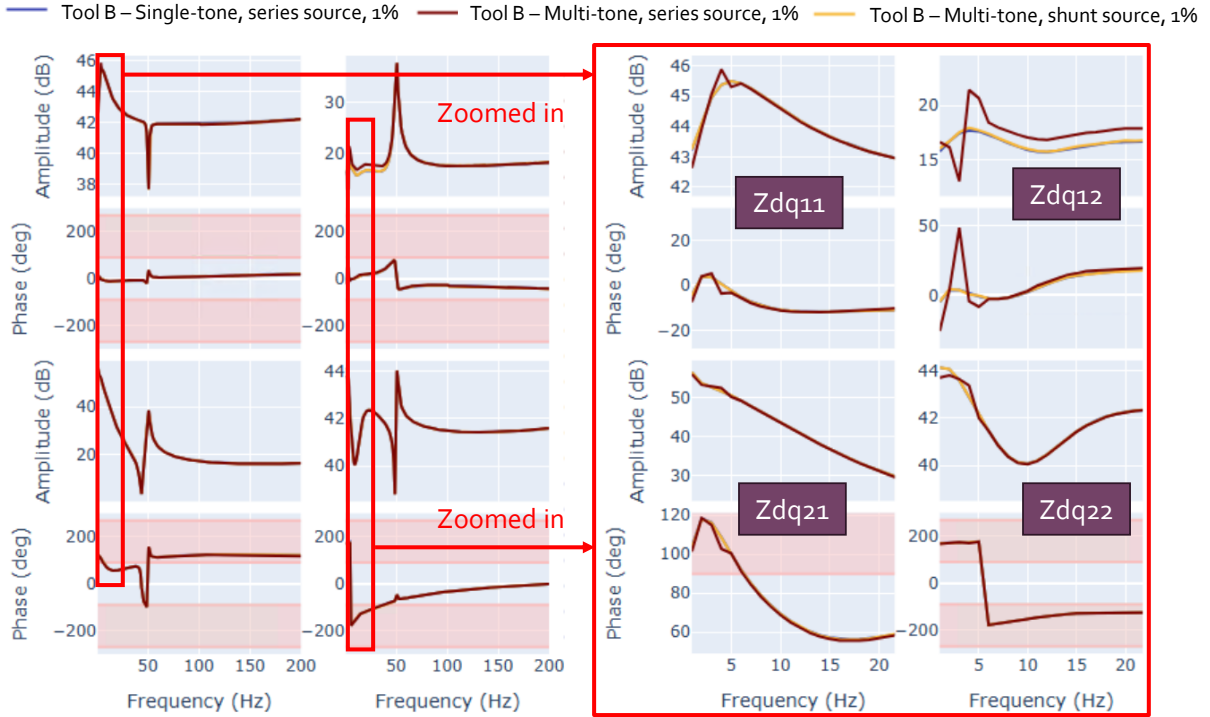


Figure 7 - Zdq scan for HVDC with different perturbation settings from Tool B

- Reveal the dependence on scan results
On the other hand, if comparing Figure 6 (a) and Figure 4 (b), both scenario applies Vac control for HVDC, though the grid conditions are different. All the other tools, B, C and D can predict the identical Zdq scans. These can reveal that the Tools B, C, D predict the DUT impedance scan independent from the grid condition. But comparing Figure 6 (b) and Figure 4 (b), it can also be seen that the Zdq scans from the Tools B, C, D are different even in the same grid condition. This indicates that the control mode can affect the impedance profile.

S2. HVDC AC scan using different perturbation parameters and configurations

The S2 case focuses on investigating the different perturbation parameters and configurations, by comparing different scan features from the Tool B. Three different scan results of Zdq for the HVDC AC scan in the strong grid condition are shown in Figure 7.

It is found that with the same perturbation size and series source perturbation, using single-tone or multi-tone injections leads to different scan results in low frequency range. Using single-tone perturbation can get a correct scan result, while using multi-tone perturbation can more easily violate the small-signal conditions, thus leading to inaccuracy. Alternatively, changing to a multi-tone shunt source perturbation with the same perturbation size works better than using a series source perturbation. This is because in this strong grid case, the grid impedance is small, and using a shunt source ensures that only small amount of current perturbation flows into the DUT side, resulting in voltage response at the perturbed frequency not too large to violate the small-signal condition. Therefore, a series voltage source multi-tone perturbation with a sufficiently small size can equally yield a correct result. It must be checked though, that the size is not too small causing numerical issues. It is worth noting that although Zab scan

results are not shown here, the finding regarding perturbation parameter sensitivity is the same, and the discrepancies are observed close to 50 Hz when using the Zab scan.

3.4 Summary of Benchmarking

The benchmarking of various frequency scan tools in two EMT tools have been done on two generic models. The key findings are summarized below

- All tools apply the same frequency scan principles to calculate impedance profiles, and most tools can derive the same scan results, no matter for AC or DC scans, MIMO or SISO scans.
- The tool implementation using forced source perturbation is found as a sensitive parameter to result in inaccurate scans.
- The control modes of PEIDs and the grid conditions can be sensitive parameters for the scanned impedance profiles, affecting if relevant couplings exist. These need to be examined when conducting frequency scan tests.
- Perturbation parameters can have an impact on frequency scan accuracy. Thus, screening right perturbation parameters to ensure small-signal conditions should be considered as part of the frequency-domain screening procedures.

4 Recommendations

4.1 Workflow of standalone frequency scan test

Based on the benchmarking study experience, a workflow for standalone frequency scans of PEIDs is recommended in Figure 8. It consists of six steps shown in Figure 8 (a), to derive a complete and reliable impedance profile for stability screening. This method ensures compliance with small-signal conditions, which is detailed in Figure 8 (b), and captures the relevant coupling phenomena, control modes and operating points for a comprehensive passivity check and/or small signal stability analysis.

In preparation for the impedance scan, **Step 1** requires a steady-state run of the EMT-simulation to verify sound simulations settings and to determine the snapshot time for the scan tool. The snapshot time should be chosen so the voltages, currents and powers have reached steady state and all relevant controllers are active. Steady-state operation of the converter is the minimum requirement for proper frequency scans.

Afterwards, it must be verified, that the perturbation does not violate small-signal-conditions of the converter system. A separate flow chart illustrates the process of **Step 2** in Figure 8 (b). Under the assumption of a resistive-inductive (RL) grid representation with no power-electronic elements, small-signal conditions can be quickly checked by verifying that the SISO scan of the grid impedance is smooth. As grid and converter in case of SISO impedance scan are coupled according to (1), discontinuities due to small-signal-condition violation at the converter often are reflected in the grid impedance where it is easy to identify such due to the clear expectation of the simple RL impedance profile.

However, a conclusive confirmation of small-signal conditions requires the comparison of at least two impedance scans with different perturbation amplitudes. If the frequency-dependent

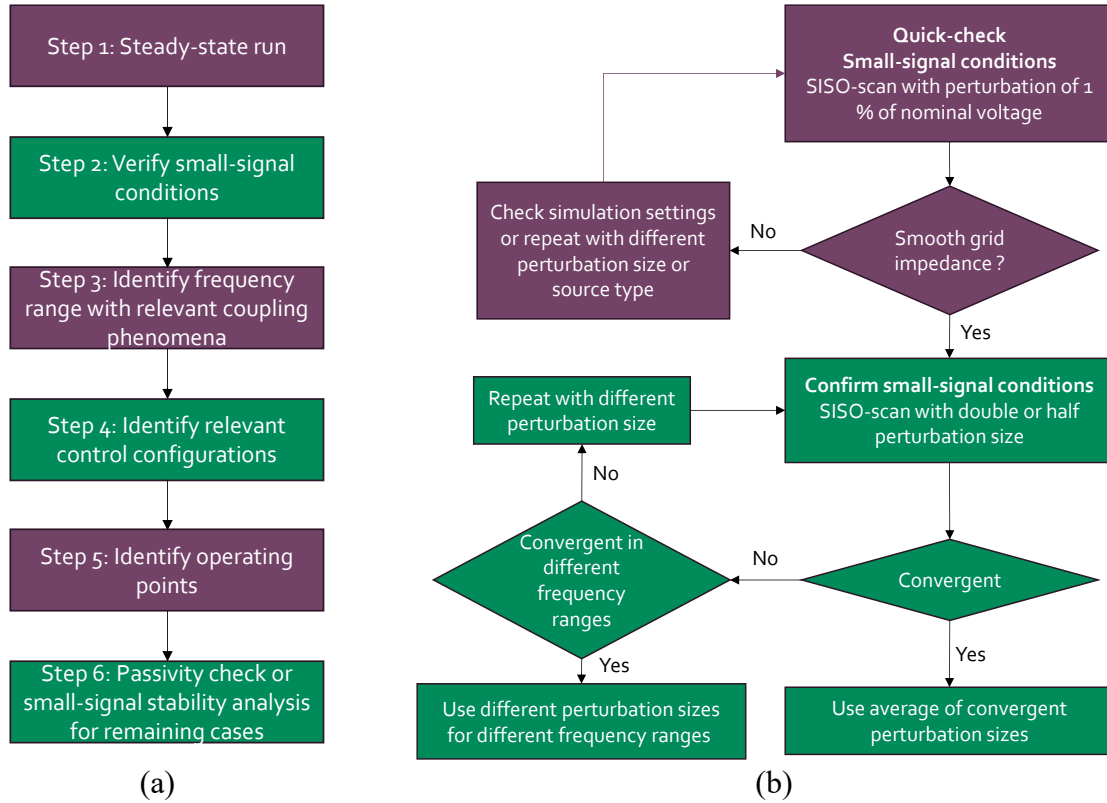


Figure 8 - (a) Standalone frequency scan procedure; (b) Detailed procedure of Step 2 to verify small-signal conditions.

impedances are equal (converge), small-signal conditions are given for both perturbation sizes and in between for the respective frequency range. This ensures that the excitation is large enough, so that also no numerical uncertainties occur. Further scans can then be conducted using a perturbation size within that interval of tested perturbation sizes. For reasons of robustness in different control modes or operating points, the average of both tested perturbation sizes is recommended. If convergence cannot be found for the entire frequency range, different perturbation sizes may be used for different frequency ranges. It is recommended to start with an amplitude of 1 % of the nominal voltage or current and then move up or down using a scaling factor of 2 or 0.5.

Assuming a passive grid equivalent, a SISO confirmation of small-signal conditions usually applies for MIMO-scans, as well. Different operating points, if not close to the boundary of the nominal operating range, usually do not violate the small-signal conditions, too. However, single-tone and multi-tone perturbations require a separate check, as demonstrated in Figure 7. A change of control modes may also have an impact. A separate check according to the same procedure is recommended.

In **Step 3** a MIMO-scan is used to determine the relevant frequency range in which coupling phenomena should be considered. On the AC-side of the converter usually frequency coupling due to asymmetric dq-controls has to be considered [12]. On the DC-side, frequency coupling can be considered irrelevant, assuming that DC-side voltage distortion is neglectable. However, the coupling between positive and negative pole or the coupling between positive, neutral and negative pole in case of bi-pole configuration needs a MIMO consideration on the DC-side [13].

These AC- and DC-side scans must be done for all relevant control modes (AC active power control, DC voltage control, Grid-forming, Grid-following, controls for reactive power, harmonic filtering, damping, ...) and different operating points (covering the typical operating range of terminal voltage, active and reactive power). Figure 6 illustrates the dependency on different control modes using AC scan examples. More detailed suggestions of operating points can be found in Chapter 7.7 in [1].

A comparison of the off-diagonal elements with the diagonal elements of the resulting MIMO impedances indicates the frequency ranges in which a MIMO representation is required. SISO representation usually suffices if the off-diagonal elements from $\alpha\beta$ -MIMO scan are much smaller than the diagonal elements.

Based on the same data, it is afterwards possible to determine which control modes and operating points must be considered in a subsequent passivity check or small-signal stability analysis (Step 6). In this sense, **Step 4** compares the MIMO impedances of the different controls with respect to each scanned operating point. If the impedances are equal, a single representative impedance suffices for the later analysis. If there is a control that yields a deviating impedance profile in either SISO or MIMO frequency range, it needs to be added to the respective analysis and increases the number of relevant scenarios. The same procedure can then be applied in **Step 5** to identify the relevant operating points analysed with respect to each control.

This pre-analysis ensures a minimum of scenarios subjected to the final **Step 6**: passivity check and small-signal stability analysis, while considering a wide range of impedance profiles of the PEID due to its control and operating point dependence. Some workflows of applying the frequency scan results for further small-signal stability screening in multi-vendor scenarios are discussed and recommended in Chapter 7.3 in [1].

In the presented workflow, Steps 2 and 3 may be conducted with lower frequency resolution for efficient screening of proper scan parameters and relevant scenarios. However, impedances used in step 6 usually require higher frequency resolution and may hence need to be rescanned. Details on the analysis of passivity and small-signal stability are outside the scope of this paper but can be found in [2].

It is worth noting that although the benchmarking studies presented here are based on generic models in this paper, the methodology is described generally, and the proposed workflow has been tested on vendor-specific models.

4.2 Useful features of tools

During the benchmarking studies of various frequency scan tools, there have been several useful tool features identified to improve the efficiency and robustness of the analysis. These features are recommended as follows:

- Steady-state check and background DFT analysis. There are not many tools that implement such a function; however, such information can be helpful for identifying the relevant frequency coupling effects from PEIDs and thus enhancing the confidence in selecting scan parameters and understanding the scan results
- Efficient handling of multiple scenarios and scan settings. Currently many tools are implemented based on a specific scenario and scan setting, which is not efficient for performing frequency scan screening in a wide range of scenarios. Automation of

efficient handling of multiple scenarios and scan settings can make it user-friendly for power system analysis.

- Frequency scan tests typically require iterative scans at various frequency points, thus long simulation time is needed to obtain sufficient data. The process can be time-demanding using offline EMT tools, which can be optimized by using paralleled cores to improve the scan efficiency.

5 Future Prospects

This paper focuses on the benchmarking of frequency scan tools as the first step of frequency-domain screening. In addition to highlighting the tool equivalence, the work reveals the sensitivity of tool implementation methods, frequency scan parameters and testing conditions, based on which a practical workflow for ensuring unified and qualified scan results is proposed. The potential further applications of frequency-domain screening are shortly discussed below.

- **Model benchmarking and validation:** the frequency-domain screening can be applied for early-stage model development, benchmarking and validation. The frequency scan tests can be used to benchmark various EMT tools, harmonic simulation models against onsite tests, offering insights in understanding the modelling and tool limitations.
- **Stability screening:** frequency scan tests can be used for further frequency-domain stability screening. Such an approach is even more promising in handling multi-vendor interoperability challenges, as it can offer insights into stability margin and even instability root causes. However, more robust screening process needs to be developed to integrate and scale the application into a wide-area power system analysis.
- **Performance evaluation and pre-qualification:** nowadays some TSOs have initiatives to consider impedance passivity as a criterion for performance evaluation or pre-qualification. In such a way, it may facilitate the grid integration process of PEIDs, as different components may be developed in modular ways with reduced interoperability risks. Further harmonization of the design and performance evaluation criteria shall be developed across the industry.
- **Grid equivalence representation:** frequency scan tests can screen the frequency-dependent dynamic behaviours at the PoC, which can be used for deriving grid equivalent frequency-domain data in future grid connection process to facilitate the design and interaction analysis for single grid connectee. However, the process today is mostly for representing grid harmonic impedance profiles, which has not yet been developed for handling interaction analysis in sub- or near-synchronous frequency range.

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