Overview, Status and Outline of the New CIGRE Working Group C4.49 on Converter Stability in Power Systems

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***Abstract*— This paper presents the overview, current status and outline of the new CIGRE working group C4.49 entitled "Multi-frequency stability of converter-based modern power systems". It provides concise definitions, a literature review covering state-of-the-art contributions, and aspects of modelling and analysis methods are discussed and aided by examples based on a proposed benchmark system. The working group's objective is to describe the phenomena, harmonize definitions and explain available methods for analyses with their advantages and disadvantages as well as providing a common understanding on modelling, analysis, evaluation and mitigation techniques. Furthermore, guidelines on the general approach to such studies and the availability as well as choice of tools will be provided by the working group.**

Keywords—CIGRE working group, converter-based power systems, impedance-based stability analysis, modal analysis, small-signal stability

I. Introduction

The electrical infrastructure is becoming more complex due to the introduction of long HVAC cables, HVDC connections, widespread penetration of renewable energy sources (e.g. PV plants, wind power plants) and offshore electrical network development. The number of power electronic converters (PV-systems, wind turbines, STATCOMs, HVDC transmission systems, etc.) in modern power systems is rapidly increasing. In the past, devices such as wind turbines or PV-systems were directly coupled to low-voltage grids and connected to medium and high voltage grids via dedicated step-up transformers. However, with the greater availability of modular multi-level VSCs, power electronic devices are increasingly directly coupled to the HV and EHV grids. This trend creates challenges such as operational coordination of grid-connected converters and small-signal stability both in the sub-synchronous and harmonic (super-synchronous) frequency regions. This is mainly due to such systems being characterized by relatively low damping and hence exhibiting resonance interactions.

No commonly-agreed methods are available for the analysis of potential sub-synchronous and harmonic (super-synchronous) stability problems. Hence, there is a need to provide a general overview of the topic, highlighting the root-cause of sub-synchronous and harmonic stability issues of grid-connected power electronic devices supported by a state-of-the-art literature survey as well as industrial experience. This paper presents the overview, status and outline of the new CIGRE working group entitled "Multi-frequency stability of converter-based modern power systems". It provides concise definitions, a literature review covering state-of-the-art contributions and aspects of modelling and analysis methods are discussed and aided by examples. The working group's objective is to describe the phenomena, consolidate definitions and explain available methods for analyses with their advantages and disadvantages as well as providing a common understanding on modelling, analysis, evaluation and mitigation techniques. Guidelines regarding the general approach to such studies and the availability as well as choice of tools will be provided by the working group.

A. Background and Motivation

The increased use of power electronic converters in electric grids has led to several incidents in the past related to control interactions. With the emergence of VSC technology, these incidents occur at both sub- and super-synchronous frequencies (i.e. up to several kilohertz). One incident that was well analysed happened in the German North Sea [7] at an offshore wind farm, connected onshore by a VSC-HVDC system. Following a switching operation on a second wind farm, oscillatory behaviour could be seen on the voltage waveform as shown in Figure 1. The oscillations looked like the presence of a 9th harmonic which is not common with that amplitude in an EHV grid. However, it turned out that the oscillation was not a typical harmonic caused by an asset with a non-linear voltage-current characteristic, but was instead caused by a control interaction, most likely due to the wind turbine reacting to a grid resonance.

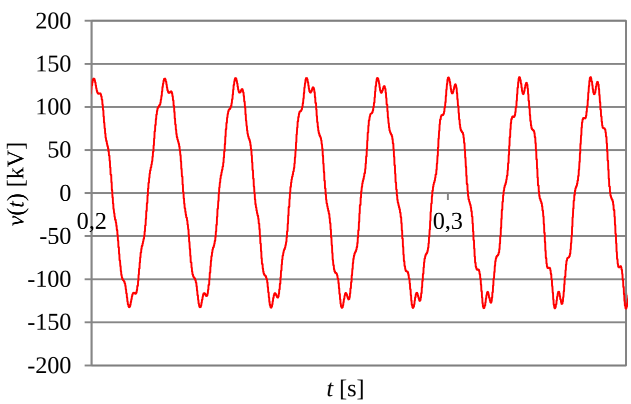


Figure 1 Measured voltage during the incident.

Due to the energization of the second wind farm, long ac cables were switched on which caused a significant shift of

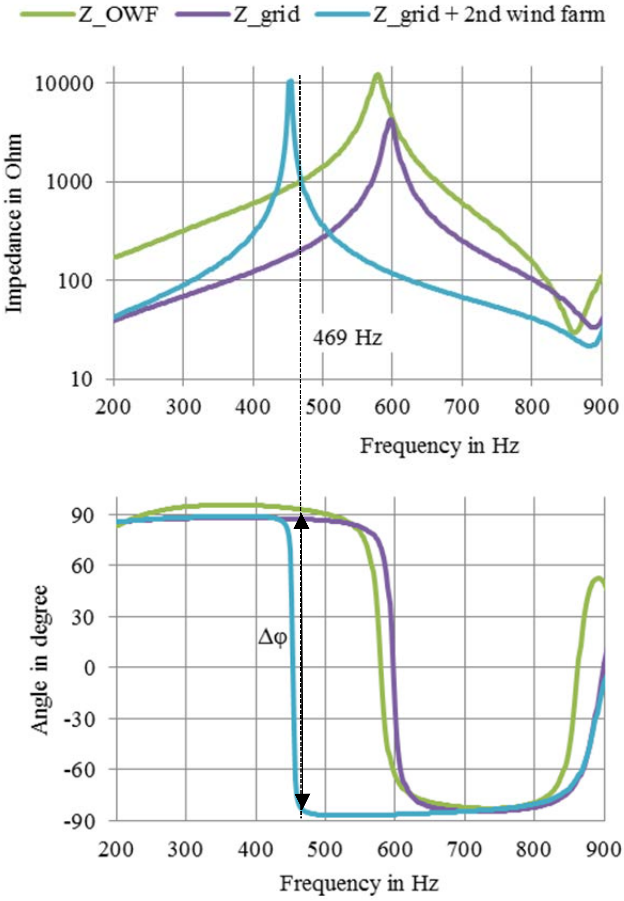


Figure 2 Impedance-based stability analysis of the offshore wind farm before and after energizing the second wind farm.

the resonance frequency in the system. Analysis showed that the wind turbine controllers in use will have stability problems with a very poorly damped resonance at this frequency. Figure 2 shows the impedance-based analysis of the incident. It illustrates that the resonance frequency drops from 600 Hz to around 450 Hz which causes the instability.

These control instabilities can happen to any grid-connected power converter and are not limited to power grids. Several other incidents were reported [7], [8], [17].

Furthermore, the interest in grid-connected converter stability analysis is increasing among power system stakeholders such as system operators, developers, connectees, manufacturers as well as academia. Therefore, several working groups are exploring this area (or recently have) to increase understanding of the associated phenomena within both industry and academia. The most relevant are listed below and C4.49 regularly takes initiative to coordinate and harmonize the work.

– CIGRE C4/B4.52 "*Guidelines for Sub-synchronous Oscillation Studies in Power Electronics Dominated Power Systems*"
– IEC SC8a TR "*Control interaction and power system damping (due to grid resonances)*"
– CIGRE B4.81 "*Interaction between nearby VSC-HVDC converters, FACTs devices, HV power electronic devices and conventional AC equipment*"
– IEC TR 61000-2-15 "*Assessment of instability/non-linear phenomena between AC-DC/DC-DC Converters and the Grid*"
– CIGRE B4.67 "*AC side harmonics and appropriate harmonic limits for VSC HVDC*"
– CIGRE B4.70 "*Guide for Electromagnetic Transient Studies involving VSC converters*"
– CIGRE C2/C4.41 "*Impact of high penetration of inverter-based generation on system inertia of networks*"
– IEEE P2800 "*Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems*", "*Wind and Solar Plant Interconnection Performance Working Group*"

II. Stability of Converter-based Modern Power Systems

A. Definition and Scope

Harmonic stability is a type of small-signal stability that is characterised by waveform distortion above and below the power system fundamental frequency. The small-signal dynamics of converters can introduce negative damping in different frequency ranges, the severity of which depends on both the controller type and the power system conditions [1]. Resonance interactions at super-synchronous frequencies will lead to high harmonics in the grid but these should not be misinterpreted as high steady-state harmonics. The phenomenon is referred to as harmonic stability and the root cause is the interaction of a converter controller with a grid resonance. This differs to steady-state harmonics which are normally observed when a poorly damped resonance is excited by a harmonic source.

a) Stability Phenomena and Frequency Range

Harmonic instability phenomena may manifest as prolonged oscillatory behaviour or instability at a frequency which may not be an integer multiple of the power system fundamental frequency. Typically, nowadays one would consider the maximum frequency up to the 50th harmonic (e.g. 2.5 kHz for 50-Hz systems) as this is stated in existing standards regarding harmonics, i.e. EN 50160, IEEE 519, IEC 61400-21 and IEC 61000-3-6. However, the bandwidth of modern converter systems is increasing and thus the instability phenomena can occur above 2.5 kHz and the behaviour should be investigated without being limited by frequency ranges proposed by standards. Moreover, in various standards (e.g. IEC 61400-21, IEC 61000-4-30, IEC 61000-4-7) the maximum frequency of 2 kHz or 9 kHz is considered as a threshold between power quality and electromagnetic compatibility. Incidentally, in the EN 50388 standard on railway applications, the upper frequency range is not defined.

B. Converter-related Dynamics

Different converter topologies and operating modes have been applied to grid-connected power electronic systems. The converter topology affects the ac-dc dynamic couplings, while the operating mode, i.e. the grid-forming or the grid-following mode, influences the small-signal dynamic behaviour of grid-connected converters.

a) Converter Topologies

For analysing ac-dc dynamic couplings, converter topologies can be classified into two groups in respect to the dc-link configuration, i.e. the central dc-link configuration for two- and three-level converters, and the distributed dc-link configuration in modular multilevel converters (MMCs). The different dc-link configurations result in different frequency-coupling characteristics. For example, the internal dynamics of MMCs, including the voltage and energy balancing at the submodule and arm levels, tend to introduce more frequency-coupling dynamics to the system stability [14].

b) Converter Operating Modes

Grid-connected converters in modern power systems are not only required to follow the grid voltage as a current source but are also expected to form the system voltage and frequency as a voltage source. However, to ride through a grid fault, current control is needed in both cases. The voltage and power control loops, as well as the grid synchronization control, are then cascaded with the current control. The cascaded control system is generally designed with multiple timescales, whose damping effect is dependent on the operating points and the grid strength. For inverter operation, the phase-locked loop has a negative damping effect which becomes more apparent in low short-circuit ratio grid conditions. In contrast, for rectifier operation, the dc-link voltage control tends to introduce negative damping in the low-frequency range. In addition, the time delay of the digital current control loop adds negative damping in the high-frequency range that can excite super-synchronous resonance.

C. Influence of the Grid

Accurate modelling of the grid significantly influences the results of converter stability studies, especially at high frequencies where damping is increased due to skin and proximity effects. This additional damping means that resonances will not reach extreme values in reality and that calculation results will be more realistic. Therefore, it does not suffice to only model assets such as transformers, lines, cables, etc., solely based on their values at nominal frequency. CIGRE joint working group B4/C4.38 “Network Modelling for Harmonic Studies” presented models for frequency dependence for a large number of different assets. These models can be used within their valid frequency range for control interaction studies.

a) Parallel Resonance due to Cables (Transient Behaviour)

Underground cables (UGCs) have a significantly higher capacitance than overhead lines and their addition to the transmission system therefore lowers system resonant frequencies. The connection of UGCs in power electronic based systems can potentially lead to critical temporary overvoltages (TOVs) and tripping of wind farms. A common cause of TOVs is the excitation of existing grid resonances. Often this situation arises during transformer energization when the harmonic-rich, high-magnitude inrush currents drawn from the grid may interact with a parallel resonance at these frequencies.

b) Influence of Cables on HVDC-LCC Links (Steady-State Behaviour)

The connection of UGCs in the transmission system alters the system impedance, resonance frequencies and short-circuit capacity and may influence the operation of existing HVDC links. In the case of HVDC-LCC, harmonic currents generated by the LCC occur predominantly at 550 Hz (11^{th} harmonic) and at 650 Hz (13^{th} harmonic) may worsen harmonic voltage distortion following any change in the system impedance. Lowering the short-circuit capacity can cause stability problems and increase the risk of commutation failures on HVDC LCC links.

c) Influence of Cables on HVDC-VSC Links and Wind Power Plants (Steady-State Behaviour)

Subsea and land cables are extensively used in HVDC-VSC links to connect (for example) onshore and offshore VSC stations. Due to the reduced filtering requirements for HVDC-VSC compared to HVDC-LCC, the active internal impedance of a HVDC-VSC link has a greater influence on harmonic interactions with the ac network than in the case of HVDC-LCC [9]. In addition, the control system heavily influences the HVDC-VSC internal impedance. Cases such as that described in [9] were found to be caused by the control interaction of the converters with the grid resonance. The resonances occurred at just a few hundred Hertz, largely due to the use of submarine cables and the poorly damped offshore system which is usually operated with very low losses.

D. Converter-based Benchmark Power System

The working group will provide simplified reference benchmark component models as follows:

- Grid-following converter – representative of converters used in photovoltaic and wind generation.
- Grid-forming converter – representative of converter systems used (for example) in battery energy storage systems or offshore wind applications.

As an illustrative example, a small-scale version of an actual ac cable connected offshore wind farm have been adapted from the original description in [10] and is shown in Figure 3. The parameter data has been derived by aggregation of the detailed data in the source such that the dynamics of the converters and their interaction with the grid are consistent with the detailed model.

The main objective of the benchmark is to provide a reference system where converter-to-converter as well as converter-to-grid interactions can be studied in a small, easy-to-model system and will be the basis for benchmarking the various methods for stability analysis that will be reviewed in the resulting technical brochure. The benchmark consists of a grid-forming converter used to collect power from a wind farm and a long ac cable. The model has been set up in the *dq*-frame to allow stability analysis with both impedance and modal approaches and allow comparison between the respective results.

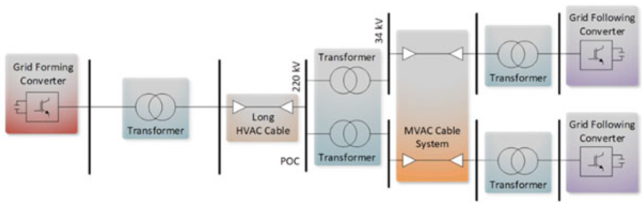


Figure 3 Benchmark power system.

Figure 4 shows simulation results for a preliminary version of the benchmark system, which in its base case state exhibits harmonic instability. This can be seen by the severely distorted phase voltage (top) taken at the point-of-common-coupling (PCC) of the grid-forming converter. The

Fourier analysis below clearly shows a significant harmonic at around 91 Hz, resulting from a harmonic instability.

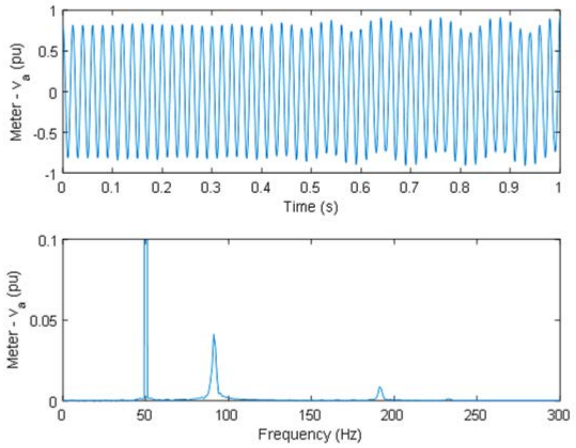


Figure 4 Benchmark system response to voltage reference perturbation applied at 0.1s.

III. STABILITY ANALYSIS METHODS

A. Modelling for Stability Analysis

a) Converter Modelling for Stability Studies

Converters operate in a time-varying, nonlinear manner; their variation over time is due to switching modulation, and the nonlinear behaviour is caused by the variable duty cycle within the closed-loop control [1]. In order to identify the causes of harmonic instability in modern converter-based power systems, the linearized modelling of power converters is required.

A general linearized modelling process firstly applies the moving average operator to the switching state variables and transforms the converter from a discontinuous dynamic system to a continuous system, where switching parasitic parameters and the deadtime effect are neglected. Then, the time-varying dynamics introduced by the ac sinusoidal operating trajectory are transformed as time-invariant dynamics by applying the Park transformation. However, this time-invariant modelling only works for three-phase balanced operating trajectories. Next, the Taylor series can be applied to linearize the nonlinear but time-invariant dynamics of converters. Depending on the methods used for the system stability analysis, the time delay involved in the digital control system may have different approximations, i.e. the exponential transfer function can be used to model the time delay in the frequency-domain analysis, while the Pade approximation has to be adopted in the modal analysis.

It is worth noting that this general *dq* modelling approach requires additional considerations for MMCs. This is due to the essential single-phase operations of MMCs, where the submodule voltage variation and circulating current dynamics tend to introduce more frequency coupling dynamics, which cannot be captured by the single *dq*-frame modelling.

For three-phase unbalanced systems, multi-frequency modelling methods are required to characterize the couplings of multiple frequency components. There are several multi-frequency modelling approaches reported in the literature [6], e.g. harmonic linearization, dynamic phasor modelling and the harmonic state-space approach. All of these methods are mathematically based on the multi-input describing function, and the harmonic transfer function matrices are formulated to characterize the dynamic couplings among multiple frequency components.

b) Frequency-dependent Characteristics of Transformers and Cables

The accurate representation of the frequency-dependent losses associated with transformers, transmission lines and underground cables is critically important for the assessment of stability-related phenomena [4]. Offshore wind farms require highly accurate models in order that damping be correctly estimated. In the case of cables, for example, accurate calculation of the series impedance and consideration of skin and proximity effects using advanced methods for use in small-signal stability assessment has been demonstrated in [4]. Incorrect estimates of damping can result in expensive over-filtering, instability and grid code compliance issues. Offshore wind farms present complex resonance behaviour due in part to the interactions of transformers, cables and reactors, which can result in low-frequency resonances. Power electronic converters may have significant harmonic emissions at lower frequencies, which if undamped, create challenges not only in terms of steady-state harmonics, but also in terms of converter stability.

B. Frequency-Domain Methods

There are two principal frequency-domain methods for analysing the stability of converter-based power systems [1]. The first method is based on the closed-loop transfer function, where the general idea is to formulate the closed-loop transfer matrices for grid-connected converters, i.e. incorporate the grid impedance into the converter control system, and then apply frequency-domain stability analysis tools to evaluate the system dynamics. The second method is impedance-based analysis, which originates from the input filter design of dc-dc converters [15], and recently emerged as a popular tool for screening the resonance characteristics of converter-based power systems.

Differing from the closed-loop transfer function approach, the impedance-based method divides the overall system into two subsystems at the bus of interest, which can be either the point of connection of the converter or a given bus of the system. The converter control dynamics are characterized at the point of connection by the disturbance-to-output transfer function, which is physically interpreted as the output admittance for grid-following converters, or the output impedance for grid-forming converters. Then, considering the grid impedance at the point of connection, a minor loop gain that is defined by the ratio of converter to grid impedance can be defined and the Nyquist stability criterion can be applied for the stability assessment [1].

A remarkable advantage of the impedance-based analysis for system operators is that no prior knowledge is required for the converter control system, and thus the “black-box” model of the converter provided by vendors can be directly applied. This fact significantly facilitates the stability analysis of large-scale power systems dominated by multi-vendor power converters. In addition, impedance modelling provides further insights into the stability impact of controller parameters, which allows a design-oriented analysis.

The frequency-domain model of grid-connected converters can be represented by either single-input single-output (SISO) transfer functions or multiple-input multiple-output (MIMO) transfer matrices, depending on the converter dynamics in the *dq*- or *αβ*-frames [16]. Consequently, either the scalar or the multi-variable Nyquist stability criterion must be used for the system analysis. Since the inner vector voltage/current control loops are implemented symmetrically on the *d*-/*α*- and *q*-/*β*-axis, the closed-loop transfer matrices of inner control loops are symmetrical, which can then be reduced to SISO transfer functions with complex space vectors. In contrast, the outer active and reactive power control loops, as well as the grid synchronization control loop, are individually applied on the *d*-/*α*- and *q*-/*β*-axis, which lead to asymmetrical closed-loop transfer matrices, and thus the multi-variable Nyquist criterion is required for the stability assessment.

Figure 5 shows sample Nyquist curves obtained by applying the multi-variable Nyquist criterion to a MIMO *dq*-frame model of a grid-connected converter. Differing from the scalar Nyquist curve for a SISO dynamic system, two Nyquist curves of eigenvalues of the return ratio of the *dq* impedances are plotted. In this case, one Nyquist curve encloses the critical point, which implies an unstable closed-loop response [17].

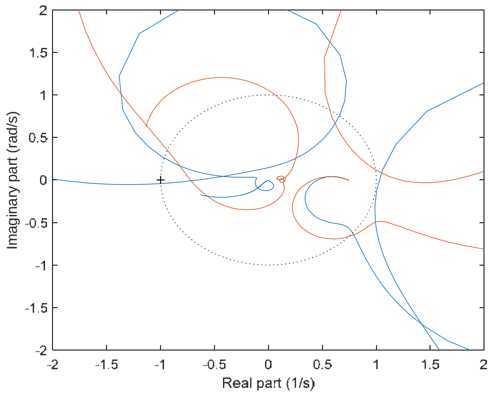


Figure 5 Nyquist curves used in the dq-impedance method (Gain margin: -5.76 dB at 157.34 Hz, Phase margin: -2.44° at 139.72 Hz).

C. Modal Analysis

Modal analysis is based on the observation that the behaviour of any linear system can be decomposed into a number of independent oscillatory and non-oscillatory modes. For harmonic stability analysis the oscillatory modes are of primary interest. Modal analysis has been used extensively for power system stability studies involving low-frequency oscillations and sub-synchronous torsional interactions. The mathematical framework used there is also applicable in the study of harmonic stability.

For power systems of nontrivial size, modal analysis is most conveniently carried out using a state-space representation of the system dynamics as described for example by [7] which also gives a detailed description of the required mathematical framework that is only briefly reviewed here. The behaviour of a dynamic system, e.g., a power system, can be described in ordinary differential equation form:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u})$$

$$\mathbf{y} = \mathbf{g}(\mathbf{x},\mathbf{u})$$

Here, **x** is a state vector composed of the state variables. This typically includes currents of inductive elements and voltages of capacitive elements, but also internal states associated with integrators in converter control systems and delay approximations. The vector **u** is a vector of external control or disturbance inputs and **y** is the output vector, typically corresponding to measurements. Modal analysis is most often carried out around an equilibrium point where the nonlinear model is linearized, yielding:

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u}$$

$$\Delta\mathbf{y} = \mathbf{C}\Delta\mathbf{x} + \mathbf{D}\Delta\mathbf{u}$$

The free motion of the system is given by:

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x}$$

Modal analysis is based on a diagonalizing coordinate transformation, which results in an equivalent state equation formulated in modal coordinates:

$$\dot{\mathbf{z}} = \mathbf{\Phi}^{-1}\mathbf{A}\mathbf{\Phi}\mathbf{z} = \mathbf{\Lambda}\mathbf{z}$$

The matrix **Λ** is diagonal, i.e., the state equations in modal coordinates are decoupled and each mode can be analysed separately. The free motion in modal coordinates is given by:

$$\Delta x_i(t) = \Phi_{i1}c_1e^{\lambda_1 t} + \Phi_{i2}c_2e^{\lambda_2 t} + \ldots + \Phi_{in}c_ne^{\lambda_n t}$$

The eigenvalues λ_i are also called system poles and describe the free motions of the individual resonance modes. Each pair of complex conjugate eigenvalues corresponds to an oscillatory mode. If the eigenvalue is expressed in Cartesian form as $\lambda_i = \alpha_i \pm j\omega_i$, then the damping ratio ζ is defined as:

$$\zeta_i = \frac{-\alpha_i}{\sqrt{\alpha_i^{\,2} + \omega_i^2}}$$

The frequency of the oscillatory behaviour in radians per second is given by ω_i. Damping is positive if α_i is negative, i.e., the complex eigenvalue resides in the left-half plane. Positive damping of a mode also corresponds to stability of that mode. Since modes may be excited by faults, background load and generation variations or harmonic injections (for example), it is crucial to retain a positive damping ratio for all modes. The phase margin of the system can be extracted from the expression:

$$\mathbf{PM} = \arctan\frac{2\zeta_d}{\sqrt{-2\zeta_d^2 + \sqrt{1+4\zeta_d^2}}}$$

where ζ_d is the damping ratio of the dominant mode, i.e., the mode with the smallest damping ratio.

Figure 6 shows sample modal analysis results for the base case of the benchmark system. Eigenvalue analysis of the system reveals a negatively damped (unstable) mode at about 140 Hz, which is related to the harmonic instability observed by simulation in Figure 4.

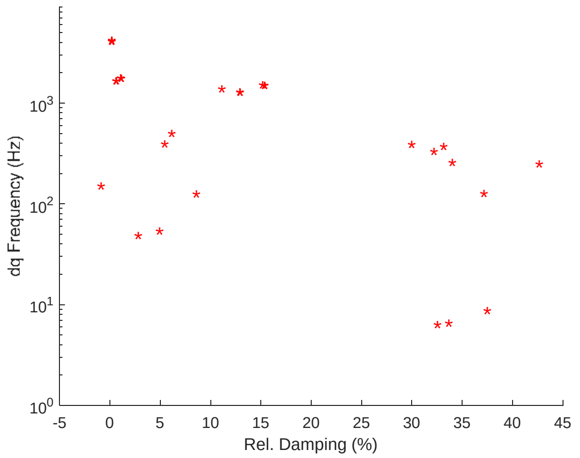


Figure 6 Sample modal analysis results for the base case of the benchmark system.

Furthermore, eigenvector and participation factor analysis can be used to determine which grid components or converters are contributing to an instability or resonance problem and help pinpoint which control parameters or modifications of grid or filter design can help alleviate such issues. Figure 7 shows participation factors of the dominant 140 Hz mode. The figure clearly reveals that the observed instability is caused by an interaction of the export cable capacitance with the voltage control loops in the grid-forming converter.

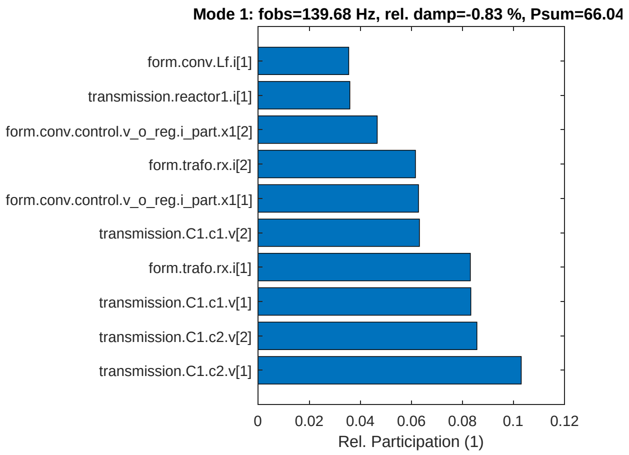


Figure 7 Participation factors of the dominant mode.

It can be noted that the results are consistent with the time domain simulation results in Figure 4 and the stability analysis using impedance analysis illustrated by Figure 5.

D. Time-Domain Analysis

The eigenvalues of the analysed system are plotted in Figure 6, where the instability is driven by eigenvalues with negative damping. The time-domain simulations from the benchmark system shown in Figure 4 could be used to validate the predicted unstable eigenvalues. The same figure also shows how the oscillatory behaviour due to instability can be measured using Fourier decomposition.

In [11] it is also seen how the damping of the most prominent modes can be estimated by inspecting waveforms for both stable and unstable cases. The timeseries / waveform analysis can also quantitatively confirm the eigenvalue-based analysis, e.g. the Prony analysis technique used for small-signal stability validation is presented in [12]. Prony is a more sophisticated technique to apply on a timeseries as it can, together with the frequency of oscillations, determine the damping.

IV. INSTABILITY MITIGATION METHODS

Following the discussion from the previous sections, the instability phenomenon and its root-cause are identified. In this section, we propose the recommended practice to mitigate such instability risk. Within C4.49, the following methods have been identified and will be further elaborated in this section:

A. Impedance reshaping of the grid-connected VSC (e.g. digital delay reduction, parameter tuning)
B. Power grid operational measures
C. Passive filter placement
D. Active damper function

A. Impedance Reshaping of the Grid-Connected VSC

The stability of a VSC, when considering its Alternative Current Control (ACC) and output filter, is mainly dictated by the inherent total digital delay and its LCL filter resonance point (in the case of MMC-VSC, it is the output L in combination with the grid/line equivalent inductance and capacitance). Digital delay compensation and LCL filter resonance damping methods can be applied to improve the inherent stable operating region. An example of tuning the active damping parameter is presented via comparison of the impedance-based analytical analysis results with the experimental time-domain results. In Figure 8, the dashed purple line (Kd=1) intersects with the grid admittance Yg (s) near 3 kHz yet the Phase Margin (PM) is above zero (i.e. less than 180° phase difference) indicating a stable system. Additionally, the dotted yellow line (Kd = 0.32) and dash-dotted red line (Kd=0) both intersect with the grid admittance Yg (s) around 2.72 kHz and the PM, for both cases, is below zero (i.e. more than 180° phase difference).

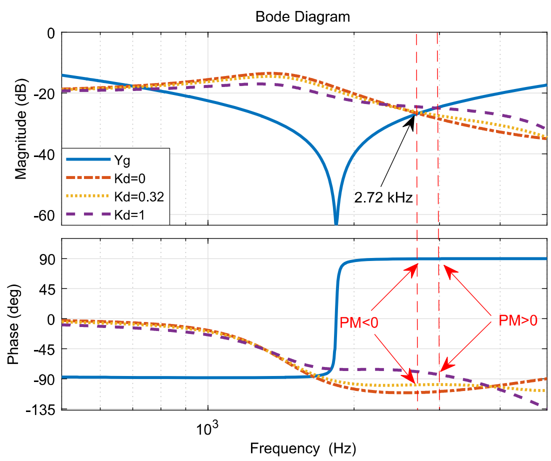


Figure 8 Impedance-based stability analysis with and without active damping in Bode diagram – grid impedance Y_g as solid blue line, VSC input admittance with K_d=0 as dash-dotted orange line, with K_d=0.32 as dotted yellow line, with K_d=1 as dashed purple line.

The experimental results of the VSC current output are shown in Figure 9 validating the impedance-based analytical results. It is evident that modifying the controller parameter can significantly improve/deteriorate the converter interaction with the power grid.

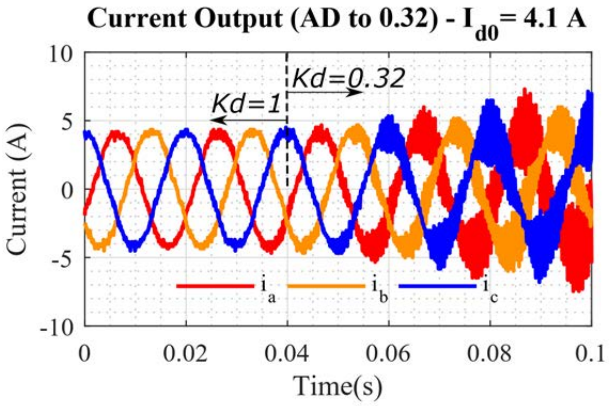


Figure 9 Experimental results of the VSC current output when K_d changed from 1 to 0.32.

B. Power Grid Operational Measures

Control interactions can often be avoided by changing the configuration of the power grid. A change of the grid configuration will always shift the resonance points in the system. If the outcome of the analysis demonstrates that a hazardous resonance point can be avoided in a specific grid configuration, then this specific grid configuration can be considered as an intermediate or final mitigation measure. The operational measures can only be chosen according to the individual situation and will always be very specific.

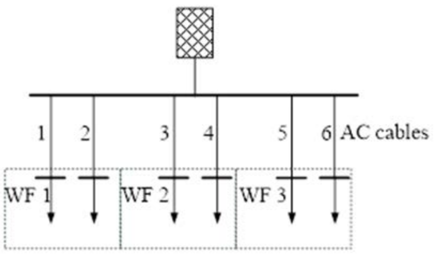
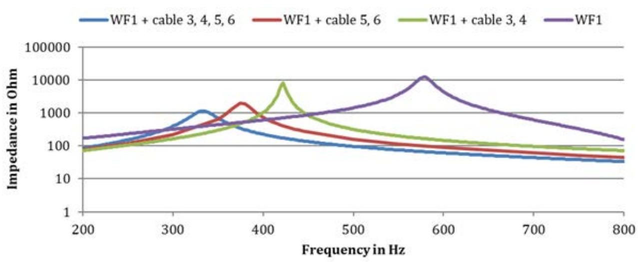


Figure 10 Example of several power electronics devices connected to a common point of connection.

An example follows of several wind farms that are individually connected by a long cable to the grid (see Figure 10). It became evident that the grid configuration with only four specific cables (i.e. 1, 2, 3 and 4) and one wind farm in operation (WF1) lead to control interactions (as presented in Figure 11). In this specific case, WF 1 was feeding energy via cables 1 and 2. To energize the other wind farms, an attempt was made to energize the remaining cables. After cable 3 and cable 4 were energized, the control interactions commenced, and the system was switched-off before any damage occurred.



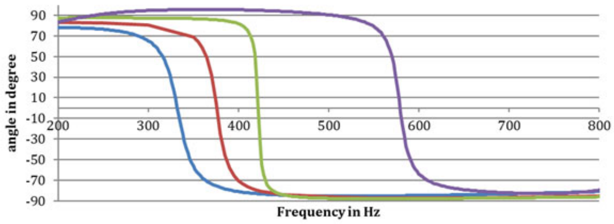


Figure 11 Frequency scans taken at cable 1 at the wind farm side for the impedance-based analysis

To overcome the above-mentioned instability phenomena, it was calculated that only the resonance around 450 Hz was critical. Simulation showed that the system would be stable if cable 5 and 6 were to be energized before cable 3 and 4.

C. Passive Filter Placement

Contrary to power grid operational measures, a high-voltage passive filter can be added to alter the resonance frequency of the power grid at the point of interest. In [13], a so-called C-type filter is applied in the high-voltage power grid to reduce the grid resonance peak near 100 Hz. By reducing the resonance peak magnitude around 100 Hz and shifting the actual resonance frequency, the potential converter control interaction with the power grid at 100 Hz can be mitigated by the installation of the carefully designed C-type filter.

D. Active Damper

The sub-synchronous control interaction (SSCI) is a phenomenon caused by the active participation of wind turbine converters, which can even occur without series-compensated transmission lines. This is because the wind turbine converter control loops play an important role in defining the impedance of a wind turbine generator. The impedance of each wind turbine generator can be reshaped by the addition of supplementary control loops. In this way the impedance of the whole wind farm can be altered. Alternatively, a shunt-connected VSC, such as a STATCOM can be utilized and provide extra damping at the hazardous resonance frequency via a grid-side damping controller (GSDC).

V. Summary and Conclusions

This paper presented the overview, status and outline of the new CIGRE working group C4.49 on converter stability in power systems. The need to harmonize methodology regarding the grid-connected converter stability in power systems was emphasized.

Together with converter modelling assumptions, the following stability analysis methods were presented and evaluated using the proposed converter-based benchmark system:

- transfer function stability analysis,
- impedance-based stability analysis,
- eigenvalue-based stability analysis,
- time domain stability analysis.

Furthermore, the CIGRE C4.49 working group will provide procedures and guidelines to industry and academia on how to perform small-signal stability studies in modern power-electronic-based power systems.

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