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TOPICAL REVIEW

Classification of Converter-Driven Stability and Suitable Modeling and Analysis Methods

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ABSTRACT The significant increase of converter interfaced generation, consumption, storage, and transmission in power systems, results in the need to consider converter-driven stability in detail, as well as to study modelling and analysis methods with which such stability effects can be represented and investigated. Due to the multiple causes of converter-driven stability effects, a classification into further categories of fast and slow converter-driven stability is necessary, which is systematically presented in this paper. We further provide a detailed overview on appropriate modelling methods including static, quasi-dynamic and dynamic modelling and their respective applications. Typical analysis methods such as eigenvalue and impedance based analysis are explained and related to the previous modelling approaches. Based on that, a guide to which modelling and analysis method is appropriate for which type of converter-driven stability, is provided. In addition, open and recent research questions with regard to studies on nonlinear analyses of large systems with acceptable computational costs are pointed out.

INDEX TERMS Converter-driven stability, converter interfaced generation, dynamic phasors, eigenvalue analysis, electromagnetic transients, impedance based analysis, participation factor analysis, power systems stability.

I. INTRODUCTION

The transformation of the electrical power system from a classical top-to-bottom structure with classical synchronous machine based power plants on the high voltage level and consumer on the lower voltage levels to a power system with mainly converter interfaced generation, consumption, storage, and transmission on high, medium and low voltage levels, leads to challenges in the power system stability. Due to the expanding percentage of power plants that are connected to the grid via power electronic devices (converter interfaced generation) and the decreasing amount of conventional plants, the dynamics of the power system significantly change. Thus, new stability phenomena can occur that must be analysed. Next to theoretical approaches that classify instability problems in power systems on the basis of the characteristics and reachability of the equilibrium points of the power system differential algebraic equations [1], extensions and revisions of the classical stability definitions of Kundur et al. [2] are introduced in [3]. In addition to the classical stability types such as rotor angle stability, voltage stability, and frequency stability, two new categories are defined, the resonance stability and the converter-driven stability. According to the definition of [3], resonance stability can be subdivided into electrical resonance stability, which is affected by the controls of doubly-fed induction generators, and torsional resonance stability. The latter is affected by flexible AC transmission systems (FACTS), which are static power electronic devices used to improve power transfer capability and controllability [4], and high voltage direct current (HVDC), which is increasingly used in transmission systems because of its advantages in long distance transmission and efficiency [5].

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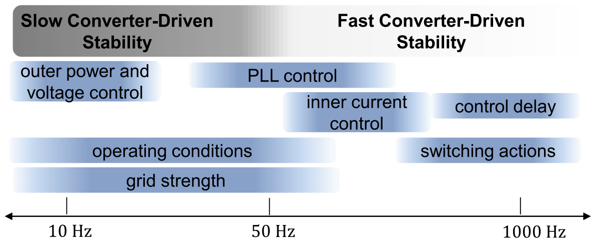

FIGURE 1. Frequency ranges of slow and fast converter-driven stability and their respective main causes for possible interactions in those regions.

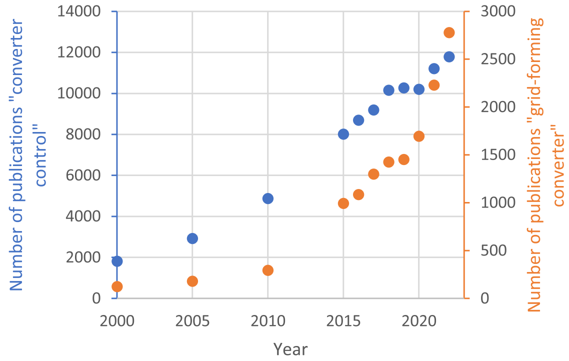

FIGURE 2. Develeopment of publications on "converter control" and "grid-forming converter."

Converter-driven stability is a generic term and summarizes all stability phenomena that are influenced or caused by converters and their controls. Thus, it is important to keep in mind that different stability phenomena are grouped and therefore the same modelling and analysis methods cannot be applied for all investigations in converter-driven stability. Occurring interactions can be assigned to different time scales. Reference [3] defines slow dynamic interactions as those with a frequency smaller than 10 Hz that concludes interactions between the controller dynamics of power electronic devices with slow responding parts of the power system. Furthermore, subsynchronous oscillations above 10 Hz or slow dynamic interactions around the fundamental frequency [6] can appear. Fast converter-driven stability includes interactions between the dynamics of the fast controllers of power electronic devices or between the control dynamics and fast responding parts of power electronic devices up to a frequency of several hundred Hz or even kHz. Fig. 1 shows main causes of slow and fast converter-driven stability and their respective frequency ranges.

Especially for analyzing and investigating fast converter-driven stability, a detailed and accurate modelling is required to be able to model the interaction phenomena. This can result in significant problems regarding the computational time and the solvability of the problem, if the dynamics and stability analyses of large power systems as transmission systems are of interest.

The increasing importance and interest in modelling of power electronic devices and stability analysis in converter interfaced generation dominated power system is reflected in the research. Fig. 2 shows the increasing amount of publications addressing the topic "converter control" and "grid-forming converter" that is increasing even more strongly with time. The timeline is based on the online available data sets of IEEE, and Elsevier (subject areas: Energy and Engineering).

The majority of the publications on converter-driven stability base their analyses on voltage source converters (VSCs). VSCs are self-commutated converters, typically based on insulated gate bipolar transistors (IGBTs). Simple topologies as 2- or 3-level VSCs allow low voltage applications. In contrast, modular multilevel converters (MMCs) with up to several hundred voltage levels, have several important advantages as modularity, scalability, good harmonic properties, and are used for medium and high voltage applications as HVDC and FACTS [7].

Overviews or guidelines for modelling and analyzing stability of converter interfaced generation dominated systems exist in the literature for various different applications with different purposes. For example, [8] gives a summarized overview on various modelling deepness and relates it to different types of stability. Based on existing literature and experiences, the paper provides a rough all-around as a good start in the topic of modelling deepness of power electronics without focusing on one specific modelling approach or stability type. In contrast, [9] defines phasor models of converters with different detail grade and compare it to electromagnetic transients (EMT) models in various studies to investigate the usability of phasor modelling approaches of power electronics for future power systems, where the dynamics cannot be clearly assigned to the electromagnetic or the electromechanical field. Advantages, disadvantages and restrictions of the modelling approaches as well as recommended actions are given. An overview on modelling methods, control approaches, and interaction between converters as well as between converters and the grid is given in [10] and in the dissertation [11] with attention to stability problems due to converter interfaced generation in distribution grids. A guideline in form of a conceptual approach for stability analysis in power electronic based power systems provides [12]. Based on system information, recommended system modelling methods and stability tools can be found to inter alia make predictions on stability regions and identify critical or instable operating points. Cheah-Mane et al. [13] provide an overview on analyzing approaches for small signal stability for converter dominated systems. Next to explanations of reference frames as the $\alpha\beta$-frame, the dq-frame or the pn-frame and the corresponding transforms, modelling examples of loads and passive elements, of synchronous generators, two-level VSCs, and MMCs are discussed. Furthermore, a short review of typical small signal analysis methods, as impedance based analysis, state space analysis, and frequency domain analysis, including advantages and disadvantages is given. Focussing exclusively on harmonic stability, [14] presents concepts, modelling and analysis for converter interfaced generation dominated systems. Kong et al. [6] focuses on small signal converter-driven stability problems, gives an inside in the state of the art research of stability challenges in future converter interfaced generation dominated power systems, emphasizes main reasons for stability problems, briefly describes the approaches of state space and impedance based analysis and gives some examples on a fully converter based two area system.

It becomes apparent that existing papers and guidelines mostly address concrete analyses and modelling types in a very detailed way, focus on specific applications or problems, or are super high level if they consider all types of stability in power systems and not only converter-driven stability. This work aims to fill the gap between detailed studies and high level power system overviews, by focusing on the classification of converter-driven stability as well as pointing out appropriate modelling and analysis methods for the respective problems. We consider converter-driven stability in general and not exclusively for a specific voltage level, but focus on VSCs, and consider those with grid-forming properties as well as those without.

The contributions we provide include the following:

1) A systematic overview and structured review on stability problems and challenges caused by converter interfaced generation and their control dynamics in the sense of converter-driven stability is given.
2) Modelling and analysis methods are presented to the reader and aim to provide a guideline for choosing the appropriate approaches to the respective converter-driven stability challenges and problems.
3) Highly topical research questions regarding converter-driven stability are highlighted.

The paper is structured as follows: Section II gives a comprehensive overview on the classification of converter-driven stability. The stability subtypes are related to their main causes and the frequency ranges in which they occur. Modelling methods of converters in terms of suitability for the study of converter-driven stability are reviewed in Section III. Section IV presents different stability analysis methods and relates it to the respective appropriate applications. Open research questions and an outlook is given in Section V before the paper ends with the conclusion in Section VI.

This paper provides a comprehensive and structured overview and guideline to suitably model and analyse converter-driven stability with priority on small signal stability. Nevertheless, it does not claim to completely cover the research work in this area.

II. CLASSIFICATION OF CONVERTER-DRIVEN STABILITY

Converter-driven stability is classified and defined in Hatziargyriou et al. [3]. This term covers all stability problems and phenomena that are caused by couplings of the dynamic control loops of converter interfaced generation with electromechanical dynamics of power system devices or with electromagnetic dynamics of power system or converter interfaced generation components. For the latter, the stability is significantly influenced by the inner current control loops and the phase-locked loop (PLL), which determines the voltage phase angle used for grid synchronization and power control [3]. Since both electromechanical and electromagnetic effects can occur, converter-driven instability problems can arise over a wide range of frequencies, from subsynchronous oscillations of a few hertz to oscillations of hundreds or kilohertz [15]. Whereas [3] makes a distinction between fast and slow converter-driven stability, we will use a more detailed division according to the main causes shown in Fig. 3.

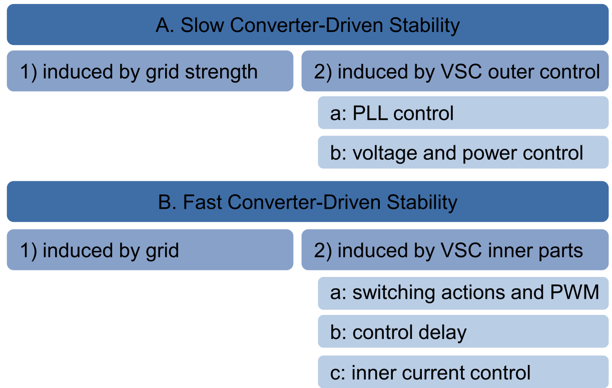

FIGURE 3. Types of converter-driven stability.

It is important to emphasize that not only stability challenges occur in the range of fast converter-driven stability or slow converter-driven stability, but interactions in different frequency ranges can occur simultaneously. In e.g. [16] 4 Hz and 30 Hz oscillations arise. Furthermore, it is relevant to mention that besides the interactions that can lead to instabilities and are addressed in this paper, interactions in power systems are obviously a prerequisite for this to work.

As stated in Section I, VSCs are considered in this work. Those VSCs can be controlled in different ways. A detailed overview and accurate definitions of possible fundamental control methods provides Rocabert et al. [17]. Grid-forming properties are present, if the converter is controlled as a voltage source, and the voltage is set. The amplitude and phase angle of the grid voltage can be specified as a function of the desired active and reactive power, or the amplitude and frequency can be specified independently. In the latter case, such a converter can exist only once per grid or extremely accurate synchronization is required. Converter that are controlled as a current source defines [17] as grid-feeding, if the power injection to the grid is independent of the grid-frequency, and as current-source-based grid supporting, if the injection is frequency-dependent. Both cases require a synchronization with the grid voltage.

Much literature as [18] makes a less detailed distinction and uses the terms grid-feeding or grid-following (GFL) for converter controlled as a current source, and grid-forming (GFM) for those controlled as a voltage source. Since the different control types are not the main topic in this paper, the simplified notation is used here. Detailed insights in different GFM control schemes, synchronization challenges, and differences to GFL control give [19], [20], [21], [22].

A. SLOW CONVERTER-DRIVEN STABILITY

Slow converter-driven stability includes the phenomena that occur in the range and below the fundamental grid frequency $f = 50\,\text{Hz}$. This involves those that can be found in literature under the terms low frequency oscillations ($< 10\,\text{Hz}$ in [16], [23]), sub-synchronous oscillations ($< 50\,\text{Hz}$), or side band oscillations (around the fundamental frequency) as in [14].

The main reasons for the slow converter-driven stability problems in converter interfaced generation dominated power systems, as induced by VSC outer control loops and grid strength, are explained in this section. Furthermore, operating conditions or VSC interfaced loads can also have an impact on the system stability and low frequency oscillations [6], [24].

Real world sub-synchronous oscillations (especially in the case of weak grids) occur and are analysed in literature. Oscillations in the range of 20 Hz-40 Hz occurred in wind farms in north-west China [25], and 2.5 Hz oscillations were detected in the transmission system in southern China [26]. An overview of further sub-synchronous oscillations real word examples in converter interfaced generation dominated systems between 2007 and 2021 provides [15].

1) SLOW INTERACTIONS INDUCED BY GRID STRENGTH

The grid strength has a significant impact on slow interactions in the sense of converter-driven stability [3].

Depending on the grid strength, different parameters differently affect possible instabilities. Especially in case of a weak grid and GFL converter, PLL parameters as PLL response time or PLL-bandwidth significantly influence possible interactions (see also Subsection II-A2a) [16], [23], [27]. It is apparent that GFL converter are prone to weak grids with low grid admittance, as stated in [28]. The synchronization of the converter via the PLL with a weak grid is also difficult [3]. Furthermore, power transfer limits [3], low voltage or high power export [23] are main reasons for slow interactions in weak grids. Power oscillations induced by weak grids in combination with static synchronous compensators (STATCOMs), which are reactive power compensation devices in transmission systems, can also occur and are analysed in [26]. Besides, a negative impact of GFM VSCs on the voltage stability is possible [29].

In contrast, strong grids in combination with GFM converters can lead to sub-synchronous oscillations in the frequency, this is investigated in [29], [28], and [30]. The latter presents new GFM converter control approaches based on filters to reduce those oscillations.

The references mentioned above all use the short circuit ratio (SCR) as a benchmark for grid strength. Since the SCR is a measure of the stability of an electromechanical generator, it is an appropriate standard for classical synchronous generator based grids, but critical to use for representing the grid strength in converter interfaced generation dominated networks. Thus, current discussions in research address the problem of using SCR as a measure and the Thévenin equivalent as a standard in future grid and propose new possibilities. Next to composite SCR [31], weighted SCR [32], equivalent SCR [33], SCR with interaction factors [33], site-dependent SCR [34], and impedance based SCR [35], recently the grid strength impedance metric was introduced in [36] where the grid strength can be determined over a wide range of frequency independently of the short circuit level.

2) SLOW INTERACTIONS INDUCED BY VSC OUTER CONTROL

VSC outer control loops as the PLL or the voltage or power control can drive slow interactions explained below as well.

a: PLL CONTROL

The significant impact of the asymmetric PLL dynamics of GFL converters on slow interactions are studied in [6]. It is shown that the pole - indicating the slow interactions - becomes positive, which indicates instability, for an increasing integral part and a decreasing proportional part of the PLL control. Furthermore, a too large PLL control bandwidth, especially when the grid strength is weak (see Section II-A1), cause low frequency oscillations [6]. The critical value of this bandwidth is investigated in [37] and it is determined that it depends next to the grid strength on the converter power setpoints. Additionally, when the PLL bandwidth exceeds this critical value, [37] observes the ability to reduce the bandwidth of a PLL of another GFL converter to enable stability.

However, the PLL is not uniquely responsible for low frequency stability problems. It is also important to consider the cross couplings between the outer controls. Thus, Subsection II-A2c shows the interactions between the PLL and the AC and DC link voltage control.

b: VOLTAGE AND POWER CONTROL

The outer control loops as voltage and power control loops of GFL VSCs and of GFM VSCs have an impact on the system stability. In case of GFL converters, the bandwidth of the outer active power control significantly influences subsynchronous frequency oscillations, especially in weak grids [38]. Interactions between the voltage control loop and outer power control loops in GFM converters can also lead to instable oscillations [39]. In [40] it is determined that those instabilities are more sensitive to the voltage and active power control than to the reactive power control. Furthermore, it is presented that a larger voltage control bandwidth can increase the stability and instabilities can be prevented by appropriate tuning of the voltage and active power control parameters. Instead of analyzing the impact of the control parameters, [41] investigates the structure of the GFM outer control loop: In case of a cascaded structured of droop controllers for the inner current control, the outer voltage and power control, the VSC tends to be less damped compared to a single droop control.

c: PLL IN COMBINATION WITH VOLTAGE CONTROL

Interactions between the PLL and the outer voltage control loop on the AC side and the DC link voltage control also contribute significantly to the low frequency stability problems, especially in weak grids. As the interactions result in reduced damping, [42] adds a state feedback controller to the current controller of a GFL VSC to achieve active damping. This enables damping that exceeds classical solution approaches based on virtual admittances by up to 50%. A detailed analysis of the couplings including control parameter sensitivities is performed in [43] with focussing on the GFL VSC voltage controllers and PLL and thus neglecting the fast inner current control. The AC voltage controller positively impacts small signal stability, particularly when voltage control gains are large, and PLL gains are small. However, the stability limit decreases due to interactions between the DC link voltage control and the PLL. It is stated that stability is principally determined by the power angle at the operation point, whereas the parameters of the DC link voltage control have only a minimal effect.

B. FAST CONVERTER-DRIVEN STABILITY

Fast converter-driven stability can occur in frequency ranges below one hundred Hz up to the kHz range. Therefore, many different instability phenomena with completely other causes are included. The root causes for fast converter-driven instability effects are interactions caused by control delays or the inner current control loop and are presented in this section. Also, VSC interfaced loads can influence such phenomena [6], but are not considered in detail in this paper.

Real world examples for fast interactions are addressed in the literature. For instance, oscillations at 97.5 Hz were observed in southern China's transmission system [26]. Oscillations with a significantly higher frequency of over 450 Hz appeared at the offshore wind farm BorWin1 that is located off the German North Sea cost [44].

1) FAST INTERACTIONS INDUCED BY GRID

Grid properties as operating conditions influence fast interactions between grid parts and converters. Furthermore, interactions between passive elements of the grid and inner control loops of the converter can lead to high frequency oscillations and harmonic instability problems [45], [46]. Those can be in the range of hundred Hz up to several kHz [8] and can occur for example in wind farms [47].

2) FAST INTERACTIONS INDUCED BY VSC INNER PARTS

Switching actions of the converters, pulse-width modulation (PWM), control delay and especially the inner current control have a huge impact on fast interactions and harmonic instability problems and are considered here in more detail.

a: SWITCHING ACTIONS AND PWM

The converter switching actions influences the resonance frequency and can shift them to critical frequency ranges, which in turn can lead to harmonic instability problems [44]. In case of paralleled converters with asynchronous carriers, the sideband harmonics from the PWM can lead to harmonic resonances and instability can occur [14], [48]. For LCL type converter, the impact of different PWMs on the high frequency switching harmonics are analysed in [49] and [50].

b: CONTROL DELAY

Converter control delays are a main reason for harmonic instability problems. Interactions can occur between the LC resonance frequency and the control delay, where the delay is typically 1.5 times the switching period time [6]. The delays require delay differential algebraic equations to be considered instead of differential algebraic equations describing classical power systems [18].

c: INNER CURRENT CONTROL

Next to the control delays, the inner current control is a further main reason for interactions leading to instability of the system [6], [8], [14], [51]. Besides the negative effects on the damping, which are transferred from the control delays to the inner current control loop [6], current limitations can provoke instabilities [52]. Additionally, a sequence decomposition algorithm that can be used for positive and negative sequence current control is a possible reason for high frequency instability problems [53]. The design of the current control loop's bandwidth also affects stability. Reference [14] explains that a VSC with a bandwidth designed for a single grid-connected converter can lead to instability problems when several of these VSCs are connected in parallel.

As already stated in II-B1, also couplings of the inner current control loop and passive grid elements can lead to high frequency oscillations and instability.

III. MODELLING METHODS FOR CONVERTER-DRIVEN STABILITY

Investigating converter-driven stability requires appropriate system modelling that is capable of representing the relevant dynamics that can cause interactions. Classical power systems dominated by synchronous generators, and thus by electromechanical dynamics with time constants greater 100 ms, have usually been modelled by using phasor models that are built of algebraic equations and suitable for representing these dynamics. The increasing penetration of converter interfaced generation leads to an evolution to faster system dynamics. Thus, modelling approaches are required that can represent those faster dynamics introduced by the converters. Typically, EMT models that consist of differential equations are used to account for fast electromagnetic dynamics. However, since small sampling times are required to capture the fast dynamics, the main drawback is that solving EMT modelled power systems are computationally extremely expensive. For large systems, solvability is sometimes impossible. Therefore, the present challenge of using suitable modelling approaches to represent stability relevant effects always involves a compromise between accuracy and computing time, or solvability.

An extensive division in seven levels of details from full physics based models (Type 1) to various EMT and phasor models to root-mean-square (RMS) power flow models (Type 7) is presented and provided in the cigré reports [54], [55]. Similar levels can be found in the guideline for choosing the right power electronics model for grid integration studies in [8]. In this section, some of these levels are combined so that the classification can be mapped to the types of simulation typically in use in the literature and in industry. We distinguish between:

- static respectively power flow modelling, typically used for grid planning and determination of operation conditions of large grids [55].
- quasi-dynamic modelling, including phasor models, which are the most common models for classical power system stability analysis, but have limitations due to the representation of faster converter control dynamics [56], and dynamic phasor models. Their main idea is to allow modelling of electromagnetic dynamics while keeping computational effort acceptable.
- dynamic EMT modelling, which are used for analyses of power electronics and small power systems, as fast converter controls can be taken into account. EMT models are also becoming increasingly important for stability analyses and grid planning of large future converter based power systems [54]. The Australian energy market operator AEMO already has large scale EMT models for all five regions of its power system, and require manufacturers to provide EMT models of the plants [57].

The applicability and suitability of those models for representing converter-driven stability effects are discussed below. As an example, a VSC is presented in each of the following sections at the respective depth of the model. Figure 9 shows an overview of the modelling levels with their advantages and limitations, extended by suitable analysis methods, considered system components, applications, and further information on the computational effort.

A. STATIC POWER SYSTEM MODELLING

Due to the fast converter dynamics, static also called steady state modelling is not appropriate for converter interfaced generation dominated power systems. Nevertheless, it is useful to build a steady state power flow model and to run a power flow calculation in advance of the dynamic analysis

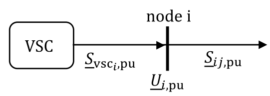

FIGURE 4. Static VSC model for power flow calculations with complex node voltage $\underline{U}_{i,\mathrm{pu}}$ and complex power flow $\underline{S}_{ij,\mathrm{pu}}$.

of the power system. $\mathbf{I}_{\mathrm{pu}} = \mathbf{Y}_{\mathrm{pu}} \cdot \mathbf{U}_{\mathrm{pu}}$ with nodal admittance matrix $\mathbf{Y}_{\mathrm{pu}}$ is solved to obtain the complex node voltages $\underline{U}_{i,\mathrm{pu}}$ in all nodes i, and the complex power flows $\underline{S}_{ij,\mathrm{pu}}$ between the nodes for the static power system model. Fig. 4 shows the VSC part of the system at node i with complex node voltage and the corresponding node power.

Calculation of the power flow enables the initialization of the nonlinear system or the operation point for linearized system model in case of a small signal analysis. Thus, the following dynamic simulation can be started in the operation point which speeds up the dynamic analysis. Furthermore, using a power flow analysis, it can be investigated if an operation point is feasible or not, and a prior analysis before the small signal analysis can be performed. Different indices can be computed to obtain a first assessment of the operational limits, since multiple different operation points can be analysed without large computational cost [58], [59].

B. QUASI-DYNAMIC POWER SYSTEM MODELLING

Quasi-dynamic power system modelling includes phasor modelling, only being capable of representing electromechanical effects, and dynamic phasor modelling, which can also represent electromagnetic transients.

1) PHASOR MODELLING

Phasor modelling can be further subcategorized into simplified positive sequence and unbalanced phasor models. In literature, next to the expression phasor models, the terms RMS models or PDT (phasor domain transients) that was recently introduced by [54] are used as well.

Phasor models are suitable to represent electromechanical effects. The electromagnetic dynamics of the grid are neglected and thus, fast system dynamics cannot be captured. In phasor models, the currents and voltages are represented as phasors in a rotating reference frame, which rotates at the nominal frequency of 50 Hz. Thus, dynamics that are around the nominal frequency are around 0 Hz in phasor models. Because of that and the neglected fast electromagnetic dynamics, greater time steps for simulation can be chosen and therefore faster simulation times and less computational effort are achieved. The grid component models as lines are simplified to constant impedance models and the system is represented by a set of algebraic equations with

$$\mathbf{V} = \mathbf{Z} \cdot \mathbf{I} \tag{1}$$

with the vector of complex node voltages $\mathbf{V}$, of complex currents $\mathbf{I}$, and the matrix $\mathbf{Z}$ containing the impedance values [9]. In the case of VSC phasor models, dynamics of the control loops can be considered, which leads to differential algebraic equations that represent the overall system.

Which control loops are taken into account depends on the selected level of detail of the phasor model, and this in turn depends primarily on the addressed problem and the trade-off between accuracy and computational effort. Commonly, the VSC itself is represented as a controllable current source (see Fig. 5) where the current magnitude and angle are controlled as it is done in [9] that provides an overview and comparison of four different detailed phasor models for VSCs. The most detailed one includes the converter outer and inner control loop dynamics as well as a RL filter representing the AC side connection dynamics, and positive and negative sequences are taken into account. Step by step, [9] first neglects the filter dynamics in the models, represents the inner current control loop dynamics as a first order delay element, then removes these fast dynamics completely, and simplifies the outer power control so that it is represented as a first order delay, too. Similar models to the first and last one just mentioned are defined and used in [60], too.

The main advantage of a smaller computational effort of simulations using phasor models than using EMT models is there, since larger time steps are possible and faster dynamics are neglected. However, it is precisely because of these idealizations that the results of phasor simulations should be treated with caution, as they can lead to supposedly better results. When choosing the time steps, the Nyquist Shannon sampling theorem should be taken into account. The time steps T_S should fulfill $T_S < \frac{1}{2 \cdot f_{\max}}$ where $f_{\max}$ is the frequency of the fastest system dynamics that should be represented [61], [62]. To be on the safe side, one can use a more conservative boundary as $T_S < \frac{1}{5 \cdot f_{\max}}$.

Typically, phasor models are used for grid-planning studies because of the straightforward initialization using the power flow solutions [8], power system stability studies, or dynamic power flow studies. The amount of literature using phasor models to study converter-driven stability is relatively small compared to that using EMT models, since the electromagnetic effects neglected in phasor models can be relevant for stability aspects in converter interfaced generation dominated power systems. Nevertheless, research focussing on phasor models for such systems exist. Publications that deal with comparison of EMT and phasor models or model reduction from EMT to phasor models exist as [9] and [60] that address the problem of computational effort for large power system stability analysis. Furthermore, [63] and [64] use phasor models for converter-driven stability analysis focussing on voltage stability, and [65] investigates the impact of grid strength and time delays on slow interaction converter-driven stability using phasor models. This is in line with the conclusion of [60], that phasor models can be used to investigate classical stability analyses such as small disturbance voltage or rotor angle stability, or using detailed phasor models incorporating inner and outer control loops, slow interactions converter-driven stability. Additionally, current approaches exist to use phasor models for power system stability analysis and exchange relevant parts that originally include fast dynamics by EMT models [54].

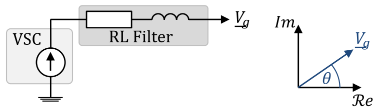

FIGURE 5. Quasi-dynamic VSC phasor model.

2) DYNAMIC PHASOR MODELLING

As already stated in [66] in 2000, using classical phasor models for representing power systems with fast dynamic phenomena can lead to inaccuracies in the subsequent analysis. Thus, dynamic modelling approaches being able to represent fast electromagnetic dynamics as dynamic phasors were introduced in literature.

Among the first publications that introduced dynamic phasor models to power systems, is [67] that applies the generalized averaging method on a PWM up-down converter. This approach of generalized averaging is later referred to as the dynamic phasor approach and has been established in the literature at least since the early 2000s [66], [68], [69]. In general, the concept of dynamic phasors is that systems with an approximately complex time domain waveform can be approximated using Fourier series with a set of time varying Fourier coefficients [66] (see Fig. 6). Dynamic phasors can be seen as an extension of phasors: Whereas phasors with time invariant Fourier coefficients can describe periodic signals, dynamic phasors with time variant Fourier coefficients are able to represent transient behavior where the system is just nearly periodic. The dynamics of the Fourier coefficients are significantly smaller than the original system dynamics and thus faster computation times can be reached, but nevertheless simulation results using dynamic phasor models can be as accurate as with EMT modelling. In [70] a ten times faster calculation time could be achieved using dynamic phasor models than EMT models for simulating the IEEE 39 bus system. Further savings in calculation effort is reachable by decreasing the level of detail of the dynamic phasors by reducing the number of Fourier coefficients used. A compromise between accuracy and computational effort must also be found here for the respective analyses. Next to the generalizing averaging method used in [54], [66], [67], [68], [69], [70], [71], and [72] and extension introduced in [73] and used under the name based frequency dynamic phasor in [74], dynamic phasor approaches applying the Hilbert transformation are used in [75] and [76]. The main goal of dynamic phasor models is to represent electromagnetic transients accurately as EMT models whereas having less computational effort. Early literature as [70] and [71] on dynamic phasors in power systems focused on this representation of electromagnetic transients. The use of dynamic phasors to model converter interfaced generation dominated power systems is mainly present in recent literature, which thematize that classical

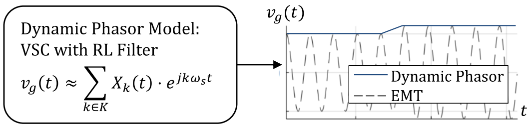

FIGURE 6. Quasi-dynamic VSC model where dynamic phasors approximate $v_g(t)$. $X_k(t)$ denotes the k^{th} time varying Fourier coefficient in complex form, and K is the number of Fourier coefficients used for the approximation [71].

phasor modelling is no longer sufficient to represent the dominant system dynamics and aim to represent the new fast dynamics whereas still enabling computability [72], [75].

C. DYNAMIC EMT POWER SYSTEM MODELLING

EMT modelling is a dynamic power system modelling approach in the time domain. In comparison to phasor modelling, real variables instead of complex ones are used. Thus, rather than solving algebraic equations, a set of ordinary differential equations has to be solved. Several different software packages with numerical solutions approaches exist. Most of them are based on the EMT program solver introduced in [77] that make use of the trapezoidal integration rule, as the programs PowerFactory [78], PSCAD [79], ATP-EMPT [80], and EMTP [81]. Next do the programs based on the classical EMT program approach using fixed time steps with fixed step size, others exist that use solvers with variable step size and require more computation time such as Matlab Simscape Electrical Toolbox [82] and PLECS [83]. The main advantages of EMT models is the capability of representing fast system dynamics from μs. Thus, detailed modelling of the electric energy systems' components with switching characteristics and nonlinearities is possible. However, those advantages in the possible accuracy also lead to the main drawback of EMT models and EMT simulations, the computation time and solvability. Due to the high accuracy and the small simulation step size that is required to represent fast dynamics, even simulations of small grids are computationally expensive. The larger the grids to be simulated, the longer the computation time, the less likely it is to be capable of performing real-time simulations, and for large systems it can also lead to the systems becoming unsolvable. The main difference to significantly shorter computations times of phasor simulations is not because of the number of calculations- this is approximately the same - but the necessity of small-time steps in EMT simulations, and the possibility to choose larger ones in phasor simulations due to the neglected fast dynamics.

But even within EMT models and simulations, different accuracies and computation times can be achieved. A definition of different types of EMT converter models depending on their accuracy is done in the cigré report [55], also comparison to phasor and static modelling relative computing times are given. According to their chosen definition, Type 2 and Type 3 converter models are suitable to perform detailed faults in converter submodels, but not grid stability studies. Type 2 uses ideal controlled switches for modelling the IGBT, and nonlinear resistances with the classical nonlinear diode characteristic for diode modelling. In Type 3, the IGBT and diodes are represented by resistances that take a small value for the closed state, and a large value for the open one. Further simplified EMT models are called Type 4, which use ideal switches for IGBT and diodes and are still capable of representing switching characteristics, but with approximately 3% of the computational effort of the detailed models. Type 2 to 4 models are also called EMT switching (EMT SW) models in literature (see Fig. 7). Next to switching models, EMT average models neglecting the high switching dynamics are commonly used. Those average models shown in Fig. 8 use controlled voltage or current sources to represent the AC and DC side characteristics [55] and exist in different levels of detail (Type 5 and Type 6). Computation times of 5% of those of Type 4 models can be reached, making the average models the most suitable of EMT models for grid studies.

In order to be able to use EMT models for large grid simulations, to be able to include and analyse electromagnetic transients caused by converters, and still be able to solve the problem in a reasonable computational time, different approaches have been introduced in the literature. Detailed and extensive work on wide area studies in converter interfaced generation dominated power systems using EMT models provides the current cigré report [54]. It is described that wide scale EMT models can be developed by using phasor converter models to incorporate them into EMT simulation frames and exchange and add all EMT relevant components by EMT models. Co-simulations platforms can be used for this purpose. They allow detailed modelling of certain devices using EMT models and data exchange with surrounding phasor models at discrete times. Additionally, phasor models can be used to perform power flow calculations to then initialize EMT models. Model order reduction of converter models is presented in [84] in order not to neglect fast dynamics and still be able to analyse fast converter-driven stability to then be used in large systems. Also [85] applies model reduction methods to EMT average models of VSCs and obtains reduced order models with different numbers of state variables and different accuracies for small signal stability analysis. The computational challenges of using EMT models for large system to achieve high accuracy, can be illustrated by real-world examples. Countries as Belgium or Denmark are affiliated to the synchronous grid of continental Europe, which was dominated by large synchronous generators. Thus, phasor models were sufficient and there was no need for large scale EMT models. However, this changes because of the significant increase in converter based generation. In contrast, the transmission system operators of Australia, Ireland, Northern Ireland, and Canada, among others, have been working on large scale EMT models for several years. The Australian energy market operator has next to EMT models for each of the five Australian power system regions, also an integrated EMT model of all regions, that uses

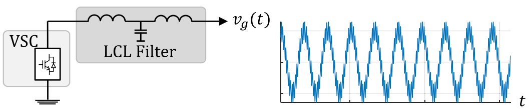

FIGURE 7. Dynamic VSC model using EMT switching modelling.

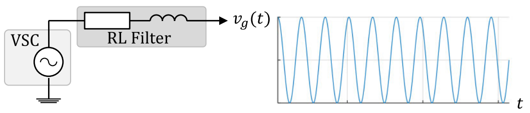

FIGURE 8. Dynamic VSC model using EMT average modelling.

advanced computation methods to enable the computation of 30 seconds simulation time within three hours [54]. To accomplish this, the method of having a phasor model of the whole power system is used in addition to the EMT model and allows for the power flow calculation to be performed and used for the EMT model initialization. In Ireland and Northern Ireland, the chosen approach is to accurately model some generation units and their control, while using a frequency dependent grid equivalent for the remaining parts of the power system [54]. Sparse matrix based EMT computation methods using transitions from power flow to time domain computations are presented in [86]. They allow the calculation of EMT models for the Hydro-Quebec power system, which contains nearly 30000 nodes.

Due to the different accuracy of EMT models, the range of application is diverse. EMT average models are usually sufficient for detailed converter control studies. Depending on the level of detail, resonance stability, slow interaction converter-driven stability [23], [87], and fast interaction converter-driven stability can be studied [26], [60] and dynamic stability limits of VSCs determined [29]. Also, when investigating AC and DC transients or if detailed cable modelling is studied [46], EMT average models can be applied. However, in all applications where effects are influenced by switching frequency harmonics, especially resonances with passive elements in the kHz range, the use of EMT switching models is necessary. Thus, studies of harmonic stability problems in the sense of converter-driven stability due to interactions of inner converter control loops and passive elements of the grid [45] or harmonic stability studies of offshore wind power plants [47] require EMT switching modelling. To represent the high frequency harmonics or resonances in the range of up to hundreds of kHz, and to modulation strategies, time steps in the range of hundreds of ns up to tens of μs are required [8]. Furthermore, full detailed switching models are applied for converter submodule error detection studies [55], or also can be used for validation purposes of EMT average, which can further be used for validation of phasor models. Besides, the use of black box models is possible using EMT models, which is important from the industry's point of view.

1) *dq*0-MODELLING

EMT simulations are often carried out as full waveforms in the *abc*-frame. However, it makes sense to switch to the *dq*0-frame, especially when considering converter control, since active and reactive parts of the current can be controlled separately, and PI controllers are well suited for controlling the DC quantities. Numerous literature as [23], [29], [88], [89], and [90] dealing with small signal stability, control, and dynamics in converter interfaced generation dominated grids base their investigations on *dq*0-models. Those models, introduced by Park, are implemented in the *dq*0-frame, also called synchronous reference frame [91]. Using the transformation matrix $\mathbf{T}$ to perform the Park transformation, *dq*0-signals can be obtained by *abc*-frame three-phase signals: $x_{dq0} = \mathbf{T}x_{abc}$. Conversely, the inverse transformation matrix is used to obtain *abc*-signals from *dq*0-signals: $x_{abc} = \mathbf{T}^{-1}x_{dq0}$. *dq*0-models bring a number of advantages, such as the decoupling of active and reactive power and the possibility to model systems correctly at high frequencies since information of the original signal remain during transformation [92]. Furthermore, the *dq*0-transformation result in time invariant models, such that small signal stability studies around an operating point are executable [92]. In case of balanced systems (systems with only positive sequences), the occurring signal variations are significantly smaller in *dq*0-reference frame than in the *abc*-frame and thus, larger time steps for simulation are allowed that leads to shorter computation times [71]. Disadvantage is, however, that non-symmetrical systems cannot be modelled using *dq*0-models [92].

Further extensive information on the *dq*0-transform, the basic concept of *dq*0-models, examples for synchronous machine and converter models, as well as a guideline on systematical construction of *dq*0-models for complex power systems is given in [92].

IV. STABILITY ANALYSIS METHODS FOR CONVERTER-DRIVEN STABILITY

Converter-driven stability and power system stability analysis is commonly done using small signal stability analysis approaches as eigenvalue analysis based on state space models and impedance based analysis. Thus, some literature that compares eigenvalue analysis methods and impedance based analysis for specific test scenarios as it is done for harmonic stability interactions in [45] or for analysis purposes of subsynchronous interaction between direct drive permanent magnetic synchronous based wind farms and weak AC grids in [25] is available. Both approaches are explained detailed in the following subsections.

Fig. 9 shows which analysis methods can be performed with which power system modelling approaches, which problems can be addressed, which components are considered, and what should be known about the computational requirements.

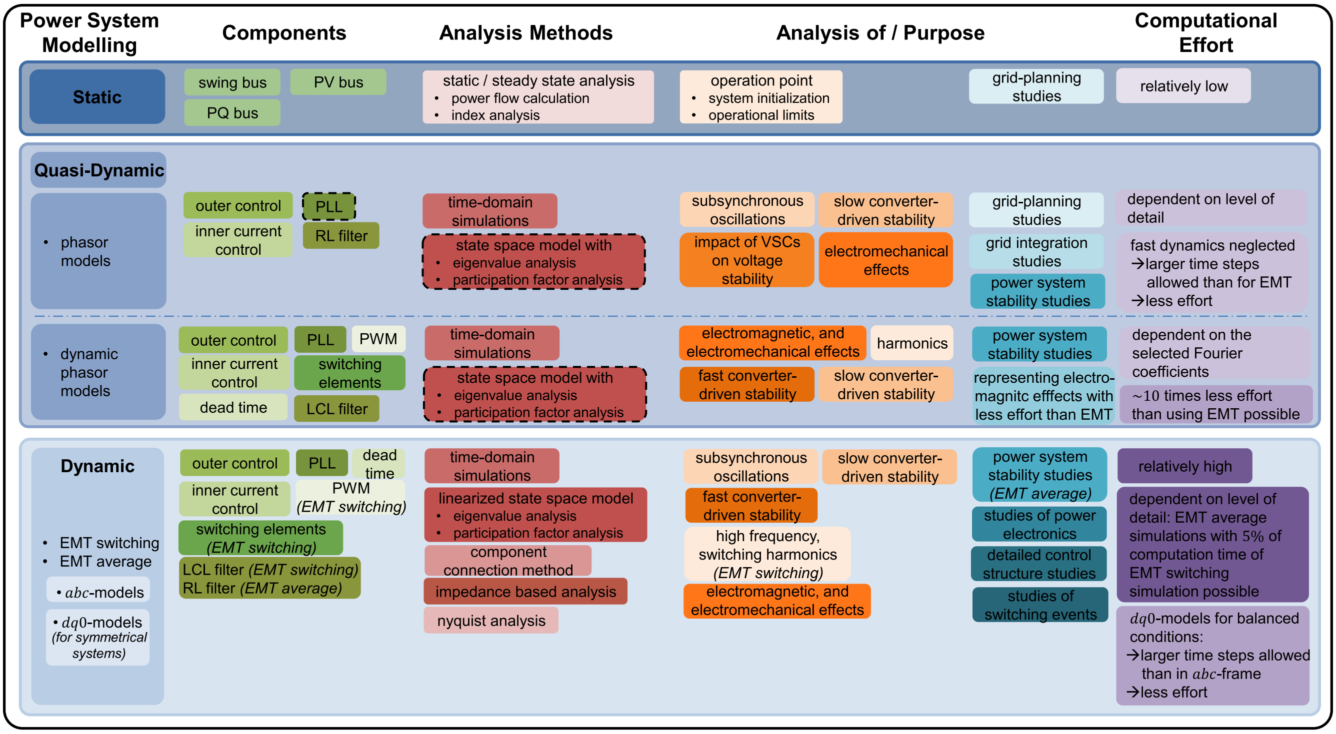

FIGURE 9. Overview of modelling methods for power systems dominated by converter interfaced generation, components considered respectively, suitable analysis tools, according analyses and purposes, as well as the computational effort. It is a guide to which modelling and analysis method is appropriate for which kind of converter-driven stability problem. The overview does not claim to be complete, but focuses on the main aspects of converter-driven stability. Black dashed boxes represent methods and elements not commonly used but occasionally found in publications.

A. STATIC ANALYSIS - PRELIMINARY ANALYSIS

Static Analysis - also called steady state analysis - is based on static power system models (see Subsection III-A). As a preliminary, it can provide important information for subsequent dynamic analyses. Performing power flow calculations is the main part of doing static analysis and leads to a deeper understanding of the operation points that will be investigated in the later dynamic analysis and if those operation points are feasible or not. Furthermore, the calculation results can be used for the initialization of power system simulation and for the linearization of nonlinear systems to obtain the linearized one at the operation point. This step saves a lot of time in the dynamic analysis.

Next to this, static analyses using indices based on power flow calculations can be performed to get an insight on the operational limits and to evaluate them. Many of such indices can be defined, depending on the objective of the investigations. Reference [93] performs a statistical static stability analysis for transmission system planning by using a voltage regulation index, a power loss index, a transmission line loading index, and a security index. Different voltage indices are used for a voltage stability analysis before a dynamic analysis is done in [59]. And [58] applies a generator angle index, a voltage index and a current index for steady state analysis.

B. EIGENVALUE ANALYSIS

Eigenvalue analysis is a popular small signal stability analysis method in power systems, since specific statements can be made about the system and the eigenvalues. The dynamic and dominant eigenvalues can be identified, participation factors of the systems' state variables can be calculated, and the input-output dynamics can be determined [12], [14]. But a prerequisite for eigenvalue analysis is that information on the system dynamics is available. Thus, no black box modelling is executable. Starting from a nonlinear system, Fig. 10 shows the general procedure to perform small signal analysis using eigenvalue analysis.

The computational effort for the eigenvalue analysis strongly depends on the order of the system matrix that further depends on the level of detail and the size of the analysed grid. Further improvements of the classical eigenvalue analysis as the Component Connection Method [94], [95] target to enhance the scalability.

Examples of eigenvalue analysis in converter interfaced generation dominated power systems are increasingly appearing in recent literature. Among others, [12], [23], [96] use eigenvalue analysis for small signal stability and interaction investigations. In [37] the Component Connection Method is used, and [24] and [72] use a sensitivity and participation factor analysis, respectively.

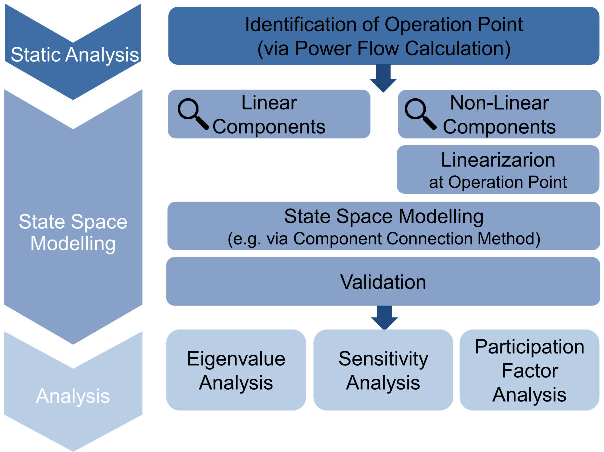

FIGURE 10. General procedure for small signal stability analysis with eigenvalue, sensistivity, and participation factor analysis.

1) STATE SPACE MODELLING

The eigenvalue based stability analysis is based on state space models. Since nonlinearities occur inter alia in the converter control loops and converter dynamics, the resulting power system models are also nonlinear systems and can be described by

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}, \mathbf{u}) \\ \mathbf{y} &= \mathbf{g}(\mathbf{x}, \mathbf{u})\end{aligned} \tag{2}$$

with $\mathbf{f} = \left[f_1\ f_2\ \dots\ f_n\right]^{\mathrm{T}}$ and $\mathbf{g} = \left[g_1\ g_2\ \dots\ g_r\right]^{\mathrm{T}}$.

By linearizing the system at the operation point, the following linear time invariant state space system is obtained:

$$\begin{aligned}\Delta\dot{\mathbf{x}} &= \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u} \\ \Delta\mathbf{y} &= \mathbf{C}\Delta\mathbf{x} + \mathbf{D}\Delta\mathbf{u}\end{aligned} \tag{3}$$

with $\Delta\mathbf{x} \in \mathbb{R}^{n\times1}$, $\Delta\mathbf{u} \in \mathbb{R}^{m\times1}$, and $\Delta\mathbf{y} \in \mathbb{R}^{r\times1}$ as state-, input-, and output-vector, respectively. $\mathbf{A} \in \mathbb{R}^{n\times n}$, $\mathbf{B} \in \mathbb{R}^{n\times m}$, $\mathbf{C} \in \mathbb{R}^{r\times n}$, and $\mathbf{D} \in \mathbb{R}^{r\times m}$ denote the system-, input-, output-, and feedtrough-matrix and are obtained by linearization around the operation point.

Different options exist to obtain a linear state space model of converter power systems. Commonly, those state space models are in the $dq0$-frame (Subsection III-C1). In the case of a nonlinear system in the form of (2), that includes all system components, the linearization can be performed for the overall system and one linearized state space system is received. This is especially practical for smaller systems, such as in [89] where the network consists of one synchronous machine, one line, load and GFL VSC. For larger networks, this approach is costly and error-prone. Here, a modular approach is advantageous. Reference [24] is one of the first papers that presents a modular approach for creating state space models of a converter based networks for small signal analysis. Therefore, state space models for the power controller, voltage controller, current controller, and output LC filter and coupling inductance are developed respectively. These are then combined to form a state space model for the converter. This is further used together with linear state space models for loads and nodes to create an overall system consisting of converters, loads, and nodes. With this commonly used type of approach, the linearization is done for the individual state space component models using the operation point determined by the power flow calculation, before the overall system model is combined on a modular basis. Determining the initial states at the operation point from the results of the power flow calculation is the difficulty in this case, since the variables of the power flow do not match the state space model variables, and therefore an optimization must be performed. In order to circumvent this problem, [96] introduces a methodology in which a nonlinear grid model is created out of nonlinear subsystems first. Afterward, the operation point that is the equilibrium point of the system and required for the linearization is calculated using Newton-Raphson method, and no power flow calculation is needed. The advantages of this method with respect to investigation of different converter control parameters are shown in [96] using the example of a system containing grid-following VSCs and a Thévenin equivalent.

2) EIGENVALUES AND EIGENVECTORS

If a linear state space model of the form (3) is available, the eigenvalues λ_i can be calculated with

$$\chi = \det(\mathbf{A} - \lambda\mathbf{I}) = 0. \tag{4}$$

If $\mathrm{Re}\{\lambda_i\} < 0,\ \ \forall i = 1, \dots, n$, the operation point of the linearized system is asymptotically stable.

However, it is not only possible to say whether stability is present or not, but with the help of root locus curves, which show the location of the eigenvalues subject to changed control parameters, critical parameter ranges can be identified. This is done in [23], [30], and [89] among other things. It should be noted that when changing parameters, the operation point may also change. Therefore, a new linearization at the new operation point is necessary before the eigenvalues are calculated again after a parameter modification.

Further approaches exist to obtain additional information on the small signal stability out of the eigenvalues, as in [97] where indices representing the impact of states and eigenvalues on system dynamics and response were introduced for stability and impact analysis of GFM and GFL MMCs on power system dynamics.

Starting from the eigenvalues λ_i of the linearized state space model, the associated right eigenvectors

$$\mathbf{v}_i = \left[v_{1,i}\ v_{2,i}\ \dots\ v_{k,i}\ \dots\ v_{n,i}\right]^{\mathrm{T}} \in \mathbb{R}^{n\times1}$$

with

$$\mathbf{A}\mathbf{v}_i = \lambda_i\mathbf{v}_i, \tag{5}$$

and left eigenvectors

$$\mathbf{w}_i = \left[w_{i,1}\ w_{i,2}\ \dots\ w_{i,k}\ \dots\ w_{i,n}\right] \in \mathbb{R}^{1\times n}$$

with

$$\mathbf{w}_i\mathbf{A} = \lambda_i\mathbf{w}_i \tag{6}$$

can be calculated for $i = 1, \dots, n$. The eigenvectors are required for a participation factor analysis that is described in the subsequent section.

3) PARTICIPATION FACTOR AND EIGENVALUE SENSITIVITY ANALYSIS

Next to the information on small signal stability obtained by using eigenvalues, information on the main reasons for instability problems can be achieved by performing a participation factor analysis. The information on the participation factor analysis and the used notation are based on [1].

Assuming that all eigenvalues λ_i are finite and different, so that $\lambda_i \neq \lambda_j, \quad \forall i \neq j$, the participation factor $\pi_{k,i}$ can be calculated with

$$\pi_{k,i} = w_{i,k} \cdot v_{k,i}. \tag{7}$$

Since the right eigenvectors $v_{k,i}$ captures the activity of the k-th state in the i-th mode and the left eigenvectors $w_{i,k}$ weights the contribution of the activity of k-th state variable in i-th mode, the participation factor $\pi_{k,i}$ measures the participation of the k-th state on the i-th mode [19]. The participation matrix contains the individual participation factors:

$$\Pi = \begin{bmatrix} \pi_{1,1} & \dots & \pi_{1,n} \\ \vdots & \ddots & \vdots \\ \pi_{n,1} & \dots & \pi_{n,n} \end{bmatrix} \tag{8}$$

In summary, participation factors can be used to determine which states influence which mode and to what extent. Thus, conclusion can be drawn about the causes of instabilities. If several state variables have a large influence on the same mode, interactions occur between these states. Reference [58] introduces indices, the interaction index to show those interactions, and the risky interaction index to evaluate if they are potentially unstable.

In addition to participation factor analysis, there also exists the eigenvalue sensitivity analysis to investigate correlations and sensitivities between states and critical eigenvalues. Starting from (5), [98] derives the sensitivity of an eigenvalue λ_i to an element $a_{k,j}$ of the system matrix $\mathbf{A}$. By differentiating (5) with respect to the element $a_{k,j}$,

$$\frac{\partial \mathbf{A}}{\partial a_{k,j}}\mathbf{v}_i + \mathbf{A}\frac{\partial \mathbf{v}_i}{\partial a_{k,j}} = \frac{\partial \lambda_i}{\partial a_{k,j}}\mathbf{v}_i + \lambda_i\frac{\partial \mathbf{v}_i}{\partial a_{k,j}} \tag{9}$$

$$\Leftrightarrow \mathbf{w}_i\frac{\partial \mathbf{A}}{\partial a_{k,j}}\mathbf{v}_i + \mathbf{w}_i\left(\mathbf{A} - \lambda_i\mathbf{I}\right)\frac{\partial \mathbf{v}_i}{\partial a_{k,j}} = \frac{\partial \lambda_i}{\partial a_{k,j}}\mathbf{v}_i\mathbf{w}_i \tag{10}$$

follows, which in turn leads with $\mathbf{A} - \lambda_i\mathbf{I} = 0$ and $\mathbf{w}_i \cdot \mathbf{v}_i = 1$ (that is valid for normalized eigenvectors) to

$$\mathbf{w}_i\frac{\partial \mathbf{A}}{\partial a_{k,j}}\mathbf{v}_i = \frac{\partial \lambda_i}{\partial a_{k,j}}. \tag{11}$$

Since $\frac{\partial \mathbf{A}}{\partial a_{k,j}}$ is zero for all elements except the ones in the kth row and jth column, it yields to

$$w_{i,k} \cdot v_{i,k} = \frac{\partial \lambda_i}{\partial a_{k,j}} \tag{12}$$

that is equal to the participation factor (7).

In general, the system matrix element $a_{k,j}$ does not correspond to the control parameter. Thus, it is worthwhile to introduce a formulation that enables the sensitivity calculation between an eigenvalue λ_i and a specific control parameter p_j: [99] did so and formulated a theorem

$$\frac{\partial \lambda_i}{\partial p_j} = \mathbf{w}_i^{\mathrm{H}}\frac{\partial \mathbf{A}}{\partial p_j}\mathbf{v}_i \tag{13}$$

with $\mathbf{w}_i^{\mathrm{H}} = \left(\mathbf{w}_i^*\right)^{\mathrm{T}}$.

In contrast, [30], [37] considers the real part σ_i of critical modes and determines their sensitivity to different controller parameters p_j with $\frac{\partial \sigma_i}{\partial p_j}$.

4) COMPONENT CONNECTION METHOD

The Component Connection Method enables efficient state space system modelling for large systems in a modular way. Since state space models for converters and their control loops can be well constructed, the application of the Component Connection Method for converter interfaced generation based power systems (as presented in [14], [37], [94]) is reasonable to reduce the computational effort. According to the Component Connection Method procedure, the power system is first divided into N subsystems, each of which is linearized individually and then represented as a linear time invariant state space model (3). Subsequently, the combination of the N linear time invariant state space subsystems using sparse interconnection matrices $\mathbf{L}_{i,j}$, that define how the in- and outputs of the subsystems are connected, leads to the state space models of the overall system.

Due to its modularity and scalability, this method is especially suitable for systems that contain similar components, such as large converter dominated power systems.

C. IMPEDANCE BASED ANALYSIS

Impedance based analyses take place in the frequency domain. A function $f(t)$ in time domain, can be transformed into a function $F(s)$ in the frequency domain using Laplace transformation. Transfer functions $G(s) = \frac{Y(s)}{U(s)}$ are defined in the frequency domain and as the ratio of output $Y(s)$ and input signals $U(s)$. Thus, analyses in frequency domain can obtain information on the system response depending on the frequency. Stability analyses in frequency domain is possible using bode diagrams with magnitude and phase plots, or Nyquist plots and criteria. In power systems represented in the frequency domain, impedances can characterize electrical devices and grids. A great advantage is, that frequency domain responses can be determined with real measurements. Therefore, impedance based power system models can be obtained - next to analytical methods - by measurements or scanning methods [100], [101]. Thus, black box models are applicable, which is also a great benefit for industrial applications, since information about internal system dynamics does not have to be published. Furthermore, converter design oriented analysis is possible and computationally more efficient [45], the scalability is high, and interaction effects between two subsystems can be analysed [12], [14]. Due to the mentioned advantages of impedance based analyses, it is a popular approach and can be found in several publications as in [14], [30], [45], [88], [100], [101], and [102].

1) IMPEDANCE SCANNING AND MODELS

As previously stated, impedance models can be created using scanning methods, also known as frequency scanning or impedance scanning methods in literature. For instance, the US National Renewable Energy Laboratory (NREL) uses automated impedance scanning techniques, which are implemented in Python, to perform impedance based analyses [103]. The impedance scan can be applied to specific components so that they can be validated and analysed individually. The general principle involves introducing a perturbation to the system at a specific frequency and measuring the impedance response, including the magnitude and phase of the element being analyzed at that frequency. This is repeated with different frequencies at sufficiently small intervals in order to obtain the impedance response over the entire relevant frequency range [104], [105]. The perturbation are applied in the voltage or current and subsequently the currents and voltage are measured for the evaluation. The further steps are explained using the example of voltage perturbations, which should have a magnitude of a few percent of the fundamental voltage and should be chosen iteratively to achieve that the measured current is neither too large nor too small. Perturbations are applied and measurements performed to the positive and negative sequence separately. Reference [88] shows that the coupling frequencies between the sequences can be neglected under most conditions. Impedance scanning can be performed using measurements that require a power source for the perturbation, as well as with EMT simulations. In both cases, stable operation is a prerequisite for injecting the perturbation. After reaching steady state again, a Fourier analysis is carried out at the respective frequencies, and the positive and negative sequences are determined. This procedure is repeated for perturbations at the different frequencies and sequences, and the impedance that is dependent on frequency can be calculated subsequently. The models determined through impedance scan can be used to validate analytical models, as demonstrated in [106].

Next to the described impedance models in the positive-negative *pn*-frame, they are often presented in *dq*-, or $\alpha\beta$-reference frame for AC power systems and are 2×2 multiple-input-multiple-output (MIMO) systems

$$\begin{bmatrix} V^d(s) \\ V^q(s) \end{bmatrix} = \begin{bmatrix} Z^{dd}(s) & Z^{dq}(s) \\ Z^{qd}(s) & Z^{qq}(s) \end{bmatrix} \cdot \begin{bmatrix} I^d(s) \\ I^q(s) \end{bmatrix} = \begin{bmatrix} 1/Y^{dd}(s) & 1/Y^{dq}(s) \\ 1/Y^{qd}(s) & 1/Y^{qq}(s) \end{bmatrix} \cdot \begin{bmatrix} I^d(s) \\ I^q(s) \end{bmatrix}. \tag{14}$$

This example is here given in *qd*-coordinates. MIMO system stability studies can be performed using the generalized Nyquist criterion presented in [107]. Reference [107] introduces a reformulation of this criterion for MIMO systems with negative feedback loop: If $\mathbf{L}(s)$ is the open loop transfer function of the MIMO system, the loci of the eigenvalues λ_i of $\mathbf{L}(s)$ can be determined with

$$\det\left(\mathbf{I} + \mathbf{L}(s)\right) = \prod_i \left(1 + \lambda_i(s)\right). \tag{15}$$

In the case that all poles of $\mathbf{L}(s)$ have a negative real part, and the loci of all eigenvalues $\lambda_i(s)$ do not circle the critical part $(-1, 0j)$, the closed loop MIMO system is stable. Furthermore, gain and phase margins that are evaluated for each eigenvalue in case of MIMO systems allow statements about stability and robustness. Common analysis methods are presented in the following sections.

2) IMPEDANCE RATIO ANALYSIS

Impedance ratio analysis is also known as the conventional impedance based methods and is based on the general principle, that a power system is divided into a voltage or current source subsystem and a load subsystem. The following information on the impedance ratio analysis is based on [108], which points out the important assumptions made and is one of the first to present impedance based analysis for converter based power systems, and on [14].

In case of conventional power systems with synchronous based generation, a Thèvenin equivalent represents the source subsystem and an impedance the load one. Assuming that

1) the source voltage is unloaded stable, and
2) the load current provided from an ideal source is stable,

the stability of the system can be determined with the Nyquist criterion where the ratio of source and load impedance or admittance represents the open loop transfer function. Since Assumption 1) is not valid in case of GFL converter based generation, the Thèveniin equivalent representation is not applicable for GFL converter systems or current source types. But, in such cases, a Norton equivalent for representing the source subsystem can be used. The assumptions

3) the current source is unloaded stable, and
4) the load powered from an ideal current source is stable,

must be fulfilled, such that the power system stability can be evaluated using Nyquist criterion with the ratio of source and load admittance or impedance. In conclusion, to maximize the stability in a voltage source system, the output impedance should be as small and the load impedance high, and in a current source system it is the other way around.

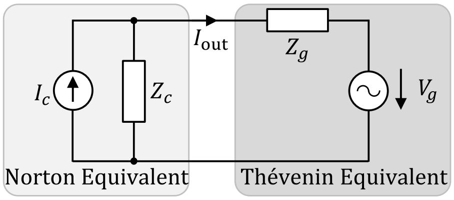

FIGURE 11. Small signal impedance based model of a converter and grid system in Norton-Thèvenin representation.

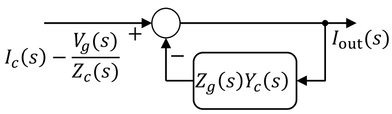

FIGURE 12. Feedback loop with open loop transfer function.

Based on these preliminary considerations, [108] introduces the presentation of a system consisting of a grid represented as the Thèvenin equivalent, and the GFL converter represented as the Norton equivalent. Fig. 11 shows the corresponding equivalent circuit. The converter output current $I_{\text{out}}(s)$ can be obtained with

$$\begin{aligned} I_c(s)Z_c(s) &= V_g(s) + I_{\text{out}}(s) \cdot \left(Z_g(s) + Z_c(s)\right) \\ \Leftrightarrow I_{\text{out}}(s) &= \left(I_c(s) - \frac{V_g(s)}{Z_c(s)}\right) \cdot \frac{1}{1 + \frac{Z_g(s)}{Z_c(s)}} \\ &= \left(I_c(s) - \frac{V_g(s)}{Z_c(s)}\right) \cdot \frac{1}{1 + Z_g(s)Y_c(s)}, \end{aligned} \tag{16}$$

with the negative feedback close loop transfer function $\frac{1}{1+Z_g(s)Y_c(s)}$ as shown in Fig. 12. Using the closed loop representation and the corresponding eigenvalues, as well the open loop transfer function $L(s)$ that is the ratio $Z_g(s)Y_c(s)$ with Nyquist analysis, lead to stability information on the system.

3) FURTHER IMPEDANCE BASED STABILITY METHODS

In contrast to the impedance based ratio analysis that considers systems represented by $Y\&Z$ or $Z\&Y$, impedance sum approaches address $Y\&Y$ or $Z\&Z$ systems [109] and general two converter or source systems, proposed in [110] in a more generic way. A further analysis method is the positive net damping criterion [111] that provides stability information in the frequency range of resonances and is therefore particularly suitable for detecting resonance instabilities. References [112], [113], and [114] present impedance based analyses methods for large systems.

4) PASSIVITY BASED ANALYSIS

The drawback of classical impedance-based stability approaches is that the analyses have to be repeated if the network impedance changes. The passivity based stability approach avoids this by taking advantage of the passivity property of a system, which holds when the real part of the input admittance is non-negative at all frequencies, that is equivalent to a phase between $-90°$ and $+90°$. In terms of converter-driven stability, this means that if the grid and the VSCs are both passive, the entire system is passive as well and therefore stable, regardless of the size of the system and the number of VSCs. However, since it is not possible to guarantee passivity for all grid elements at all frequencies, the passivity of the VSCs is only requested for critical grid resonances, and thus instabilities caused by the VCS are unlikely to occur [115]. Critical resonances include subsynchronous resonances with frequencies between the fundamental frequency and twice the fundamental frequency, which are mainly impacted by outer control loops such as the PLL and power control, and high-frequency resonances with hundreds of Hertz up to the Nyquist frequency. Time delays and the interactions between the current control and the LCL filters influence the latter [116]. A further influence on the stability is the sequence decomposition algorithm used for positive and negative sequence current control of the VSCs. This is analysed in [53] and the second order generalized integrator based sequence decomposition algorithm is recommended. While the majority of publications on passivity based analyses in VSCs is for the GFL case, [117] looks at how a general design criteria can be established for a GFM controller with single loop voltage control, and passivity can be ensured up to the Nyquist frequency.

V. OPEN RESEARCH QUESTIONS AND OUTLOOK

Several open research questions remain and appear in modelling and stability analysis in the sense of converter-driven stability.

- New control approaches of VSCs and new VSCs of different vendors [118], launched on the market, require that further research is constantly carried out and modelling and analysis approaches are further developed and adapted in order to be able to analyse the respective scenarios appropriately.
- Due to the very recent research in the field of GFM control, possible interactions caused by GFM VSC are of special interest in future, too, and are considered in first publications as [29], [30], [52], [58], and [119].
- Since of the nonlinear converter dynamics, small signal stability analysis based on linear state space models, as described in this paper, will not be able to capture all relevant information and effects. Thus, nonlinear analyses approaches as nonlinear state space model analysis for converter interfaced generation dominated systems presented in [96] will be crucial in future.
- Improvements in impedance based methods, as participation factor analysis performed in [102], that enable more concrete statements on interaction causes than classical impedance ration analysis, offer the promise of combining more accurate stability analysis with the advantages of the impedance based method.
- Papers on small signal stability, mentioned in this work as [14], [65], [88], and [89], mainly focus on small scale systems. General stability effects that have been

detected in small systems can also be transferred to large systems. However, not all effects that occur in large systems or multi converter systems can be recognized when only study small networks. Furthermore, classical small signal analyses methods can cause problems in case of larger systems, caused of large system matrices that requires too many computational efforts or are not solvable at all.

- In order to be able to investigate large systems, model order reduction methods as in recent papers [60], [84], [85] also play a significant role. They must meet the requirement that the most important dynamic behavior of the converters can still be represented.
- Due to the increasing amount of offshore wind parks, HVDC connections, FACTS, and storage power plants, the penetration of power electronic devices also increases in the transmission system level. Also here, converter control induced interactions [120] and oscillations, both synchronous [15], [26] and high frequency ones [121] can occur.
- The increasing number of VSCs and the resulting significant changing system dynamics require control methods that are robust against these changes. In recent studies by the authors, GFM control approaches are analysed for this robustness.

In summary, it can be said that there is a need to develop methods that allow nonlinear analysis to be carried out on large systems with reasonable computational effort, in order to study the interactions driven by inverters in these systems. Research in this area and close cooperation with industry, including system operators and manufactures, is needed to enable an increased penetration of converter interfaced generation to meet the European Union's climate targets while ensuring power system stability.

VI. CONCLUSION

This article gives an extensive overview on different kinds of converter-driven stability. It further reviews the most recent and common modelling and analysis approaches for converter interfaced generation, consumption, storage, and transmission dominated power systems, and a guideline which modelling and analysis methods are suitable for which type of converter-driven stability problem is developed, with focus on the modelling level of detail and respective computation time. Based on the literature review, the most important recent and future challenges regarding converter-driven stability, appropriate modelling and analysis are elaborated and presented in this work.

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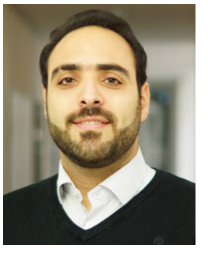

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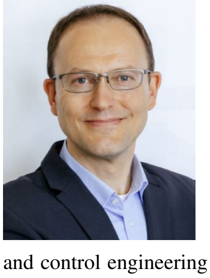

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