Impedance-Based Stability Analysis of Multi-Parallel Inverters Applying Total Source Admittance

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Abstract—The utility-scale wind and solar electricity production is typically connected to the power grid through multiple parallel three-phase inverters. One of the main issues in such grid-connected systems is the harmonic resonance caused by interactions between the grid and inverters. A common method for the analysis of these systems has been the impedance-based stability criterion. However, in systems that have multiple parallel inverters, the system complexity and challenges in obtaining the required impedance measurements may deteriorate the accuracy of the impedance-based approach. This paper discusses the aggregation of parallel inverters and the stability analysis of such grid-connected system. A simple method, based on impedance measurements, is shown for defining the allowable number of paralleled inverters so that the system remains stable. Experimental results are shown from power hardware-in-the-loop setup recently developed at DNV GL Flexible Power Grid Lab.

Index Terms—Stability analysis, Impedance measurement, Grid-connected inverter, Parallel inverters, Power hardware-in-the-loop

I. INTRODUCTION

The electrical power system is changing rapidly, as the electricity production shifts towards inverter-interfaced sustainable options, such as solar and wind power [1]. This causes inherent change in power system dynamics, as the inverters operate over a wide frequency range with little to no internal inertia. This has shown to cause stability and power-quality issues especially in weak grid conditions and in grids with high power-electronics penetration [2]–[4].

The stability assessment of systems that have high number of grid-connected inverters are usually carried out either by state-space based methods [5]–[7] or by applying impedance-based stability criterion [8]–[11]. The methods have different approach: state-space methods permit the complete assessment of the global system, while the impedance-based stability criterion is limited to the local interface [12], [13]. The impedance-based stability analysis is based on the ratio of the equivalent grid impedance and inverter output impedance. However, as the method is interface-dependent, the selection of the interface affects the indicated stability margins [10], [14]. The implementation of the impedance-based stability assessment is simple for single inverters, but in multi-inverter systems the interface selection is not as intuitive and the impedance measurements are more difficult to obtain.

The large-scale solar and wind power plants consist of multiple inverters, as the unit power is limited to a few megawatts. Consequently, the plants typically have complex structures, which introduces new challenges in using the impedance-based stability criterion. Fig. 1 shows a schematic diagram of n parallel three-phase inverters connected to the
power grid through a common bus. In such a system, assessing the impedance-based stability at the output interface of a single inverter may be insufficient. The absolute stability in the system is mutual, but the indicated stability margins at different interfaces may differ drastically. For a system shown in Fig. 1, the sources can be aggregated, and the stability analysis can be carried out for source-load subsystems.

This paper applies the impedance-based stability criterion for systems comprising multiple paralleled inverters. Experimental results are provided by using power hardware-in-the-loop experiments performed at DNV GL Flexible Power Grid Lab in high power range (50 kW). Additionally, a simple method is shown for predicting the system robustness for \( n \) parallel inverters based on measurements of a single device, which can be used as a guideline for designing plants with multiple inverters. The stability is assessed based on multi-input multi-output (MIMO) impedance measurements [15] and applying sensitivity function, generalized Nyquist criterion (GNC), and closed-loop system poles.

The remainder of the paper is organized as follows. Section II briefly reviews the theory of the impedance-based stability analysis of grid-connected inverters in synchronous reference frame. In Section III, a MATLAB/Simulink case study demonstrates the presented stability assessment methods for paralleled inverters connected to a shared point of common coupling (PCC). Section IV presents the experimental power hardware-in-the-loop setup (DNV GL Flexible Power Grid Lab, Arnhem, Netherlands) and impedance measurements of parallel devices. In addition, the stability margins of a system that has \( n \) identical inverters are evaluated and discussed. Finally, Section V concludes this paper.

II. THEORY

A. Synchronous Reference Frame

Synchronous reference frame has been widely applied to simplify control of three-phased AC system, where the frame of reference rotates at the grid frequency describing the balanced three-phased sinusoids as two constant values (d and q components). The transformation is carried out by a multiplication with Park’s matrix to direct, quadrature and zero-components, respectively. In balanced systems, the zero component is omitted. The DC-valued signal has a steady-state value, and can be linearized for small-signal analysis and controlled with conventional PID-controllers. The synchronous reference frame voltage, current, and impedance are matrices given as

\[
V_{dq}(s) = \begin{bmatrix} V_d(s) \\ V_q(s) \end{bmatrix}, \quad I_{dq}(s) = \begin{bmatrix} I_d(s) \\ I_q(s) \end{bmatrix}, \quad Z_{dq}(s) = \begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix}
\]

where the off-diagonal elements in the impedance matrix represent the cross-couplings \( Z_{qd}(s) \) and \( Z_{dq}(s) \) between the d and q components. For the remainder of this paper, the Laplace variable \( s \) is omitted from the equations.

B. Impedance-based stability criterion

Fig. 2 shows an example in which a single inverter (source) is connected to a power grid (load). The source is modeled by a Norton equivalent circuit, as a current source \( I_s \) in parallel with the source impedance \( Z_s \). The load voltage is denoted by \( V_l \) and the load impedance by \( Z_l \). This combination applies for a grid-parallel inverter in which the grid acts as a voltage type load and the inverter resembles a controlled current source. Assuming that the source is stable when unloaded and that the load is stable when powered by an ideal source, the stability and other dynamic characteristics of the interconnected system can be determined by applying the impedance ratio of the source and load [8]. The impedance-based characteristic equation for the interface can be written as

\[
[I + Y_o Z_g]^{-1}
\]

where \( Y_o \) is the inverter output admittance, \( Z_g \) is the grid impedance, and their product \( Y_o Z_g \) is the minor loop gain [16]. The small-signal characteristics of the interface between the systems resemble a feedback system, and the small-signal stability of such three-phase AC system can be assessed by examining its closed-loop poles and the characteristic loci [17].

C. Dq-domain impedance measurements

The impedances of the load and source subsystems can be measured by either voltage- or current-type injection. Recent studies have presented methods in which an excitation signal is injected to the system (for example, to controller reference) and the output currents and voltages are measured and Fourier-transformed [15], [18]. The frequency-dependent dq-domain impedance is defined as

\[
V_{dq} = Z_{dq} I_{dq}
\]

The impedance (or admittance) matrix can be calculated from the Fourier transformed voltages and currents. In order to reliably measure the impedance of an inverter, the device should operate at nominal operation conditions.

Orthogonal broadband binary signals have been proposed for efficient impedance measurements of power-electronic systems in the dq domain, as the signals are easy to generate and can obtain the complete impedance matrix directly with a single measurement cycle [15]. In this work, two orthogonal binary injections are applied for obtaining the complete impedance matrix. The injections are generated by applying a Hadamard modulation, presented in detail in [15]. The first signal is injected into d channel and the second signal into q channel, while the frame angle is aligned to the local reference frame. The combination of orthogonal injections allows MIMO measurement, where all components are obtained.
simultaneously. In shunt injection, the interconnected load and source subsystems affect the impedance measurements of each other, as the current perturbation to source causes voltage response, which acts as a perturbation for load subsystem (and vice versa). This is an inherent phenomenon when measuring interconnected systems with shunt injection. The same occurs in series injection unless the injection is made with ideal device with no impedance.

D. Admittance aggregation of parallel inverters

The impedance-based assessment does not work straightforwardly in systems that have multiple inverters; the system may contain multiple possible choices for interface selection on which the analysis is performed [12]. In addition, the required impedance measurements and models may be very difficult to obtain due to complex system topology. A system that has multiple parallel inverters can be simplified if the impedances between the inverters can be assumed small. In this case, the inverters are connected to the same PCC with zero interconnection impedance. The inverters share the same synchronous reference frame, so they can be aggregated by adding the inverter admittances together. Fig. 3 shows the equivalent circuit for \( n \) parallel inverters connected to the same PCC, where the inverters are depicted as Norton equivalents and the grid is Thevenin equivalent (see Fig. 2). The paralleled current sources and impedance elements can be joined to a single current source and parallel impedance, which is the conventional source-load system for impedance-based stability analysis. Thus, the impedance-based stability criterion can be directly applied for parallel inverters at the same PCC with the aggregated total source admittance given as

\[
Y_o^{\text{tot}} = \sum_{n=1}^{N} Y_o^n
\]

E. Stability analysis based on minor loop gain

As the impedance ratio resembles a feedback system, the impedance-based dynamics are similar to conventional closed-loop systems. The equivalent loop gain is the minor loop gain \( Y_o Z_g \) (source-load impedance ratio). Thus, multiple methods can be used for stability analysis, which all describe the same stability interpretation, but have differences in the areas of emphasis. A conventional approach is to use Nyquist criterion, where a graphical presentation shows the absolute stability of a single-input-single-output (SISO) system. In [17], a generalized Nyquist criterion was applied for impedance-based stability analysis in the dq-frame (MIMO system). The path of Nyquist contour related to the critical point \((-1,0)\) shows the absolute stability. Another widely used method is the sensitivity function of a control loop, which can be extended to MIMO systems. In order to describe the sensitivity of a MIMO system, singular value decomposition (SVD) can be used to obtain the singular values (SV) of the sensitivity matrix [6]. As the interest is on maximal SV, only the upper SV is applied in this work. The MIMO sensitivity function is given by

\[
S = \text{svd}[(I + Y_o Z_g)^{-1}]
\]

The stability assessment can also be carried out based on system transfer functions. The transfer functions are usually obtained by analytical small-signal modeling, which may be difficult or time consuming. Another approach is to fit the measured data to a parametric model. The transfer functions can be acquired by matrix fitting [19], [20], where the frequency-dependent impedance-ratio is approximated by matrices equivalent to state-space representation given by

\[
Y_o Z_g = C(sI - A)^{-1}B + D + sE
\]

which can be expressed with residual matrix representation

\[
Y_o Z_g = \sum_{m=1}^{N} \left( R_m \frac{1}{s - a_m} \right) + D + sE
\]

The system eigenvalues, equal to closed-loop poles of the impedance-based feedback system, can be obtained from the estimated MIMO transfer function. The poles give an analytical representation of the impedance-based dynamics by providing resonant frequencies and corresponding system damping factors. In this work, the transfer functions are estimated for providing an auxiliary stability analysis by assessing the system eigenvalues.

III. SIMULATIONS

The simulations are performed in MATLAB/Simulink with averaged models of identical current-fed inverters shown in Fig. 4. The inverters operate in a cascaded control scheme with a DC-voltage controller, AC-current controller, and phase-locked loop (PLL). A case of four parallel inverters without interconnection impedance is considered. Table I presents the control parameters of the inverters.

The measurements are performed with a shunt injection at the common PCC interface. The grid impedance and the inverters’ total impedance are obtained by measuring the node voltages and the currents to the grid and to inverters. The minor loop gain is given by a ratio of grid impedance and inverter impedance. The impedance was measured for systems that had either 1, 2, 3, or 4 identical parallel inverters.

The stability of the system under study is assessed based on the shunt impedance measurements with GNC where the eigenvalue trajectories (eigenloci) indicate the stability margins. The minor loop gain is a 2x2 matrix and has two
TABLE I  
SIMULATION PARAMETERS FOR INVERTER AND GRID.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Grid frequency</td>
<td>$f_n$</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Base power</td>
<td>$S_b$</td>
<td>2.7 kVA</td>
</tr>
<tr>
<td>Base voltage</td>
<td>$V_b$</td>
<td>207 V</td>
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<tr>
<td>Power factor</td>
<td>$\cos\phi_{conv}$</td>
<td>1.0</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$f_{sw}$</td>
<td>8 kHz</td>
</tr>
<tr>
<td>Nominal power</td>
<td>$S_{conv}$</td>
<td>1.0 p.u</td>
</tr>
<tr>
<td>DC capacitor reactance</td>
<td>$X_{Cdc}$</td>
<td>0.11 p.u</td>
</tr>
<tr>
<td>L-filter reactance</td>
<td>$X_{L1}$</td>
<td>0.052 p.u</td>
</tr>
<tr>
<td>L-filter resistance</td>
<td>$R_{L1}$</td>
<td>0.006 p.u</td>
</tr>
<tr>
<td>DC voltage</td>
<td>$V_{dc}$</td>
<td>2.0 p.u.</td>
</tr>
<tr>
<td>Grid reactance</td>
<td>$X_g$</td>
<td>0.071</td>
</tr>
<tr>
<td>AC current control proportional gain</td>
<td>$K_{PCC}$</td>
<td>0.0149</td>
</tr>
<tr>
<td>AC current control integral gain</td>
<td>$K_{I_{CC}}$</td>
<td>23.442</td>
</tr>
<tr>
<td>DC voltage control proportional gain</td>
<td>$K_{P_{VC}}$</td>
<td>0.0962</td>
</tr>
<tr>
<td>DC voltage control integral gain</td>
<td>$K_{I_{VC}}$</td>
<td>1.2092</td>
</tr>
<tr>
<td>PLL control proportional gain</td>
<td>$K_{P_{PLL}}$</td>
<td>1.5520</td>
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<tr>
<td>PLL control integral gain</td>
<td>$K_{I_{PLL}}$</td>
<td>156.32</td>
</tr>
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</table>

IV. EXPERIMENTS

The experiments are performed with power hardware-in-the-loop (PHIL) setup developed at DNV GL Flexible Power Grid Lab. Fig. 8 shows the setup diagram, which consists of eigenvalues. In the analysis, the eigenlocus which bypasses closer to the critical point is considered the critical eigenlocus. Fig. 5 presents the GNC loci of the minor loop gain for systems that have different number of inverters. The figure shows that increasing the number of paralleled inverters drastically reduces the stability margins of the system, as the locus approaches the critical point. In addition, it can be predicted that a fifth parallel inverter would destabilize the system. The same conclusion can be drawn from the sensitivity function shown in Fig. 6, which shows peaking in system sensitivity when more inverters are connected.

In order to test the predicted system robustness, simple step tests are performed for varying number of paralleled inverters. The q-channel current reference of a single inverter is stepped from 0 to -2 A (corresponds to $Q = 0.2$ p.u. reactive power) at 1.0 s for systems that have 1 to 4 inverters. Fig. 7 shows the transient responses to PCC voltages in phase domain (upper envelope). A clear deterioration in the response appears when additional parallel inverters are added.

![Fig. 4. Overview of system that has four paralleled inverters.](image-url)

![Fig. 5. (a) Critical eigenloci and (b) zoomed critical eigenloci of the system with 1, 2, 3, or 4 parallel inverters.](image-url)

![Fig. 6. Maximum singular values for systems with different number of parallel inverters.](image-url)
Fig. 7. PCC voltage responses to current reference step test.

an OPAL-RT real-time digital simulator and 200 kVA Egston digital power amplifier, which has four groups of four single-phase units. The units contain six interleaved parallel half-bridge inverters (equivalent switching frequency is 125 kHz) and have closed-loop bandwidth of 5 kHz. A high-speed communication link feeds the references from OPAL-RT to Egston, and the current and voltage measurements are sent to OPAL-RT every 4 μs from the amplifier. In this work, one group provided stiff grid voltages and groups 2, 3 and 4 were configured to emulate a three-phase grid-connected inverter with current controller (CC) and phase-locked loop (PLL) (see [21]). The three parallel inverters had a total nominal power of 52 kW shared evenly. Table II presents the setup parameters.

TABLE II
EXPERIMENTAL SETUP PARAMETERS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid frequency</td>
<td>( f_g )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Egston amplifier maximum power</td>
<td>( S_{\text{max}} )</td>
<td>200 kVA</td>
</tr>
<tr>
<td>Nominal main voltage (RMS)</td>
<td>( V_n )</td>
<td>325 V</td>
</tr>
<tr>
<td>Power set point for inverters</td>
<td>( P_{sp} )</td>
<td>20.6 kW</td>
</tr>
<tr>
<td>Power factor for inverters</td>
<td>( \cos(\phi) )</td>
<td>1.00</td>
</tr>
<tr>
<td>D-current reference</td>
<td>( i_d^* )</td>
<td>50 A</td>
</tr>
<tr>
<td>Inverter 1 L-filter</td>
<td>( L_1 )</td>
<td>2.0 mH</td>
</tr>
<tr>
<td>Inverter 2 L-filter</td>
<td>( L_2 )</td>
<td>0.5 mH</td>
</tr>
<tr>
<td>Inverter 3 L-filter</td>
<td>( L_3 )</td>
<td>3.2 mH</td>
</tr>
<tr>
<td>PLL proportional gain</td>
<td>( K_{\text{PLL-P}} )</td>
<td>0.3482</td>
</tr>
<tr>
<td>PLL integral gain</td>
<td>( K_{\text{PLL-I}} )</td>
<td>21.88</td>
</tr>
<tr>
<td>Inverter 1 CC proportional gain</td>
<td>( K_{\text{CC1-P}} )</td>
<td>6.4247</td>
</tr>
<tr>
<td>Inverter 1 CC integral gain</td>
<td>( K_{\text{CC1-I}} )</td>
<td>2019</td>
</tr>
<tr>
<td>Inverter 2 CC proportional gain</td>
<td>( K_{\text{CC2-P}} )</td>
<td>1.6514</td>
</tr>
<tr>
<td>Inverter 2 CC integral gain</td>
<td>( K_{\text{CC2-I}} )</td>
<td>518.8</td>
</tr>
<tr>
<td>Inverter 3 CC proportional gain</td>
<td>( K_{\text{CC3-P}} )</td>
<td>10.070</td>
</tr>
<tr>
<td>Inverter 3 CC integral gain</td>
<td>( K_{\text{CC3-I}} )</td>
<td>3162</td>
</tr>
</tbody>
</table>

A. Total admittance of parallel devices

The PHIL setup is capable of admittance measurements, where the voltage perturbation is injected to the grid voltages through voltage references of the grid-emulating group. A multi-input-multi-output (MIMO) measurement scheme is used, where the first orthogonal sequence is injected into the d component and the second orthogonal sequence into q component of the grid voltages. The first injection was 2047-bit length and the second 4094 bits. Both sequences were generated at 5 kHz. The injection amplitudes were selected to be 1% of the nominal current or voltage values. The measurements using the first injection was averaged over 100 periods, and the measurements using the second injection over 50 periods (because the length of the second sequence is, by definition, doubled compared to the first sequence). Thus, the measurement time for obtaining the complete 2x2 impedance matrix was 41 seconds. Fig. 9 shows the measured MIMO admittances for each inverter. The inverters are not equal due to differently sized output L-filters (0.5, 2, and 3.2 mH) and different current controller parameters (the PLL controllers are identical).

In order to validate the admittance aggregation of parallel devices, the three inverters are measured together. This is compared to the calculated sum of inverter admittances. Fig. 10 shows the measured total impedance (orange) and calculated reference from the separate measurements (black). The measurement accurately follows the predicted sum of admittances, except for the distorted low-frequency cross-couplings. The result verifies the hypothesis of admittance
aggregation of distinct devices connected to the same point of common coupling. When the impedances of transmission cables and transformers between the inverters can be assumed small, the stability analysis can be performed based on the aggregated total admittance and grid impedance. Thus, the stability margins and limitation to maximum number of parallel devices can be straightforwardly obtained.

**B. Stability prediction for parallel identical devices**

In many cases, a large-scale plant consists of multiple identical inverters connected to a grid. Impedance measurements of the complete system are usually difficult to obtain, and more convenient analysis methods are required. This section presents a method for assessing the stability and robustness of multiple parallel inverters based on admittance data from a single inverter and grid impedance. Based on the proposed method, guidelines for system design can be derived by considering the required stability margins. The uncertainty of impedances in connections inside the system and possible inaccuracy or variance in grid impedance can be accounted for with simple sensitivity analysis, where, for example, an error margin of ±10% is given to grid impedance.

The deterioration of system robustness is demonstrated by calculating the stability margins for \( n \) parallel identical inverters. The grid impedance in this example is \( Z_g = 0.08 + j\omega 0.0004 \, \Omega \). Fig. 11 shows the grid impedance \( q \)-component (black) and aggregated inverter impedance (blue to red) for \( n = 1 \ldots 10 \) parallel inverters (the measurements and analysis are performed for complete 2x2 matrices, but only one component is shown here for simplicity). The simplified reduced-order impedance comparison shows that the crossing point in impedances shifts to lower frequencies where the phase difference is greater when \( n \) increases.

Based on generalized Nyquist criterion (GNC), the stability analysis for MIMO systems can be performed by examining the characteristic loci. If the loci encircles the critical point and the system has no RHP zeros, the system is unstable. Fig. 12 shows the characteristic loci obtained by solving minor loop eigenvalues for systems that have \( n = 1 \ldots 10 \) parallel devices, where only the critical contour (that is, closer to the critical point) is shown. The figure clearly shows that the critical contour approaches the critical point when \( n \) increases. The same information can be extracted from the MIMO sensitivity function (4) shown in Fig. 13.

In order to evaluate the system time-domain properties
more comprehensively, the system transfer function can be estimated by fitting a pre-defined model to the measured closed-loop return ratio. Once the transfer function is acquired, the poles and zeros of the closed-loop system can be solved analytically. In this example the fitting was performed by MATLAB `tfest`-tool. Fig. 14 shows the critical poles of the MIMO system, which are located in the (2,2)-component of the full-order matrix for varying number of inverters. The pole-zero map confirms that introducing more parallel inverters shifts the system poles towards imaginary axis, which changes the frequency and damping of the resonant modes present in the system. Based on the pole-zero map and GNC loci, it can be predicted that 11th parallel inverter would destabilize the system as the damping of the critical resonant mode would be almost zero. Table III shows the frequencies and dampings of the critical pole pairs as a function of number of paralleled inverters.

![Fig. 12. Critical generalized Nyquist contour of \( n = 1 \ldots 10 \) paralleled inverters.](image1)

![Fig. 13. MIMO sensitivity function of \( n = 1 \ldots 10 \) paralleled inverters.](image2)

![Fig. 14. Pole-zero paths of the closed-loop system when the number of parallel inverters increases from 1 to 10.](image3)

**TABLE III**

<table>
<thead>
<tr>
<th>( n )</th>
<th>Critical pole pair</th>
<th>Frequency (rad/s)</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(-208.01 \pm 180.66)j</td>
<td>323.214</td>
<td>0.829</td>
</tr>
<tr>
<td>2</td>
<td>(-202.14 \pm 209.87)j</td>
<td>291.386</td>
<td>0.694</td>
</tr>
<tr>
<td>3</td>
<td>(-152.89 \pm 214.96)j</td>
<td>263.786</td>
<td>0.580</td>
</tr>
<tr>
<td>4</td>
<td>(-116.00 \pm 210.82)j</td>
<td>240.626</td>
<td>0.482</td>
</tr>
<tr>
<td>5</td>
<td>(-87.96 \pm 203.05)j</td>
<td>221.284</td>
<td>0.398</td>
</tr>
<tr>
<td>6</td>
<td>(-66.24 \pm 194.01)j</td>
<td>205.007</td>
<td>0.323</td>
</tr>
<tr>
<td>7</td>
<td>(-49.13 \pm 184.74)j</td>
<td>191.160</td>
<td>0.257</td>
</tr>
<tr>
<td>8</td>
<td>(-35.46 \pm 175.65)j</td>
<td>179.194</td>
<td>0.198</td>
</tr>
<tr>
<td>9</td>
<td>(-24.4 \pm 166.82)j</td>
<td>168.594</td>
<td>0.145</td>
</tr>
<tr>
<td>10</td>
<td>(-15.0 \pm 158.51)j</td>
<td>159.218</td>
<td>0.094</td>
</tr>
</tbody>
</table>

**C. Discussion**

The stability analysis of a grid-connected system that has multiple parallel inverters often becomes complex and even unfeasible. While it is possible to accurately model all components of the system and analyze the stability with state-space models or with impedance models, the computational requirements are very high and time-consuming. When the impedances between the paralleled inverters can be assumed small, a more straightforward approach can be taken as shown in this work. However, the uncertainties in the analysis should be taken into account when defining the minimum stability margins. A simple sensitivity analysis on variance in grid impedance or additional impedance from transformers can be performed as an additional method.

**V. CONCLUSION**

The impedance-based stability analysis has been extensively applied to stability assessment of grid-connected inverters. This work has studied the stability analysis for grid-connected systems that have multiple parallel inverters. The complete modeling of such complex systems is often infeasible and obtaining accurate impedance measurements at relevant interface may be difficult. If the impedances between the parallel connected inverters can be assumed small, the inverters share the synchronous reference frame, and the total source admittance can be calculated based on measurements or impedance models of separate devices. This work has presented admittance summation of parallel devices and demonstrated the deterioration in stability margins as more parallel devices are connected to a shared point of common coupling. Based on impedance measurements of a single device, the stability margins are predicted for systems that have \( n \) identical inverters. The stability is assessed by applying generalized Nyquist criterion, sensitivity function, and closed-loop poles of the source-load impedance ratio. The method indicates the maximum number of paralleled devices at a given grid interface, as well as the system damping ratio at the main resonant frequency. The presented methods can be used for stability prediction for systems that have multi-parallel inverters.
This research and testing has been performed using the ERIGrid Research Infrastructure and is part of a project that has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No. 654113. The support of the European Research Infrastructure ERIGrid and its partner DNVGL is very much appreciated. The work was also supported in part by the Academy of Finland.

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ACKNOWLEDGEMENTS

This research and testing has been performed using the ERIGrid Research Infrastructure and is part of a project that has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No. 654113. The support of the European Research Infrastructure ERIGrid and its partner DNVGL is very much appreciated. The work was also supported in part by the Academy of Finland.

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