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Impedance-based Stability Analysis of Grid-tied Converters Integrated with BESS using DC Impedance Models

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Background and Objectives

- The purpose of this project is to evaluate the DC-link voltage stability of a grid integrated BESS converter based on the proposed DC impedance models.
- The dynamics of a phase-locked loop (PLL) plays a significant role in grid-tied converter system stability.
- With integrating BESS and renewable energy sources into the power grid, power converters need to be connected in parallel. Due to this interconnection among the converters with a common DC bus, the equivalent impedance of the DC network, i.e., DCNI of these parallel converters, may vary and can cause oscillations in the DC link voltage (DCLV).
- DC impedance models (DCIM) are proposed for different control modes of the grid-integrated BESS systems with PLL dynamics.
- DC-link voltage stability analysis of grid-tied converter is evaluated using proposed DC impedance models, including DCNI variations.
- Finally, the analytically developed models are validated using hardware-in-the-loop (HIL) testing.

Impedance based stability analysis

- From Figure (1), an impedance-based stability analysis of a grid-connected inverter can be analyzed in two ways. (i) Z_{in}/Z_{dc} ratio. (ii) Z_g/Z_{pcc} ratio. The system is stable if the ratio satisfies the Nyquist stability criteria.
- Referring to Figure (1b), the DC link voltage is expressed as (1).

$$V_{dc} = \frac{1}{1+\frac{Z_{in}}{Z_{dc}}} V_{in} \qquad Z_{dc} = \frac{v_{dc}}{i_{in}} \qquad (1)$$

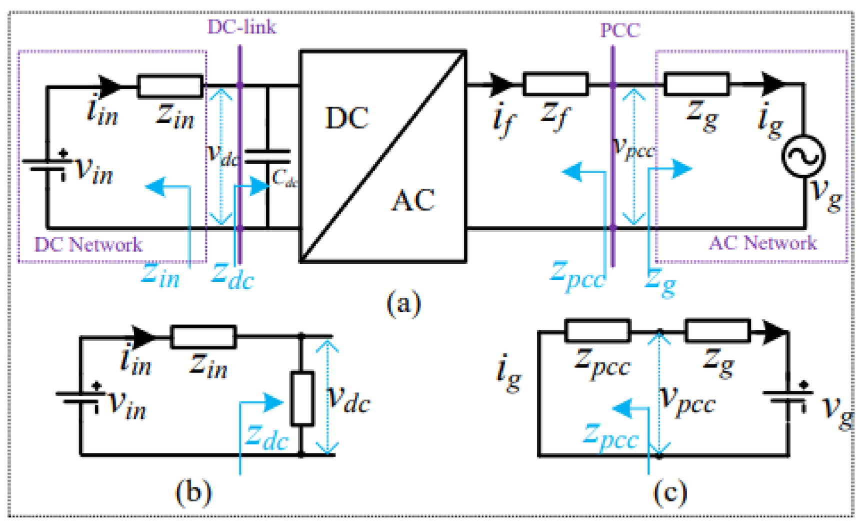

Figure (1) – Block diagram of (a) a typical DC to AC interface for connecting an AC network and DC network from a small signal impedance perspective, (b, c) An equivalent representation of the entire system seen from the DC side and the AC side, respectively.

Proposed DC Impedance models

- The block diagram of the grid-tied converter system integrated BESS with the controller is shown in Figure (2).
- For different control objectives, Z_{dc} characteristics are distinct.

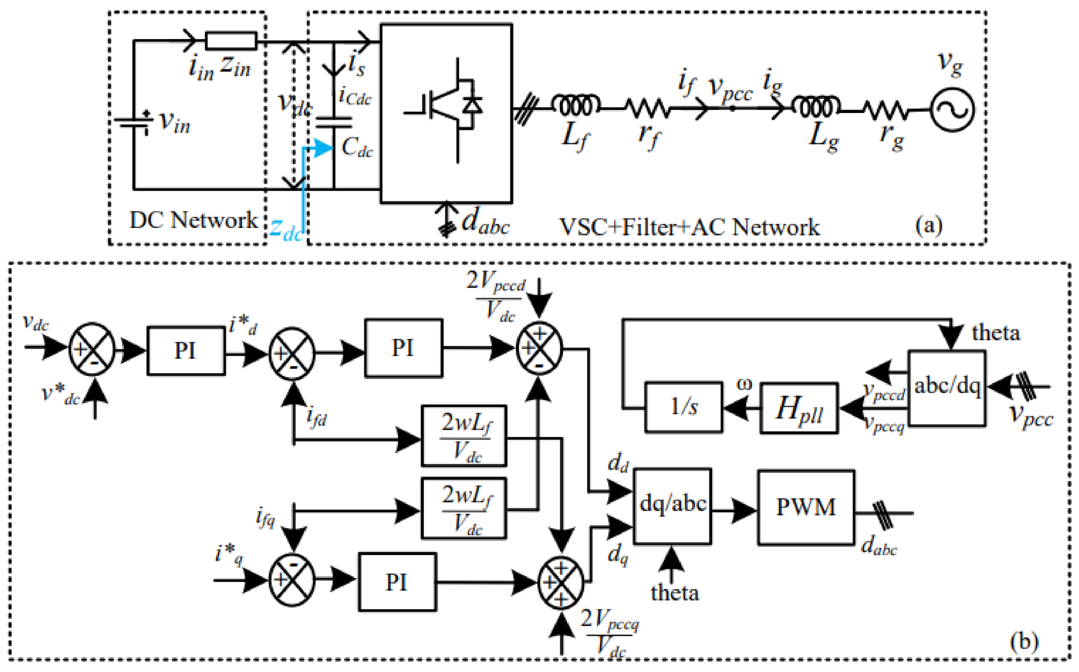

Figure (2) – Block diagram of (a) Three phase DC–AC converter with DC and AC networks and (b) DC link voltage controller and PLL.

- The DC impedance models of open loop control, closed loop *dq* current control, and closed loop DC link voltage model control with PLL dynamics for a grid-tied converter with BESS are given by (1)-(3).

$$Z_{dc-ol-pll} = \frac{\hat{v}_{dc}}{\hat{i}_{in}} = \frac{1}{C_{dc}s + \left(\frac{3}{4}\left[(I_f^{dq})^T G_{PLL}{}^d Z_g + (D^{dq})^T\right](Z_g + Z_f - \frac{V_{dc}}{2} G_{PLL}{}^d Z_g)^{-1} \frac{1}{2} D^{dq}\right)} \qquad (2)$$

$$Z_{dc-cl-pll} = \frac{\hat{v}_{dc}}{\hat{i}_{in}} = \frac{1}{C_{dc}s + \frac{3}{4}\left[(D^{dq})^T + (I_f^{dq})^T M_3\right] (M_4)^{-1} \frac{1}{2} D^{dq}} \qquad (3)$$

$$Z_{dc-vl-pll} = \frac{\hat{v}_{dc}}{\hat{i}_{in}} = \frac{1}{C_{dc}s + \left(\frac{3}{4}\left\{\left[(D^{dq})^T + (I_f^{dq})^T M_3\right] (M_4)^{-1} M_5\right\} + \frac{3}{4}\left\{(I_f^{dq})^T G_5 H_{v1}\right\}\right)} \qquad (4)$$

Hardware-in-the-Loop Validation

- Bode plot analysis is used to analyze the proposed impedance models. Table 1 shows the parameters of the system used in this study.
- The Typhoon hardware-in-the-loop testbed is used to validate the proposed impedance models, and the setup is shown in Figure (3).
- By examining the Bode plot and test result in Figure (4), it is clear that the intersection frequency of two impedances is the same as the DC side resonance frequency.
- In addition, when the converter's duty ratio is higher, oscillations are not due to the resonance on the DC side.
- Figure (5) shows that in dq current control, DCIM interacts with DCNI in and around the PLL bandwidth, resulting in oscillations in DCLV. This oscillation causes unstable operation of the converter.
- Similarly, in the DCLV control of grid-integrated BESS from Figure(6), DCIM interacts with DCNI around the PLL bandwidth, causing the converter to become unstable.

Table I – System Specifications

Parameter	Value Considered
Grid Voltage	230 V
Filter, Grid Inductance	2.6 mH, 1.3 mH
Filter, Grid Resistance	0.77 Ω, 0.38 Ω
DC Link Voltage	750 V
PLL, Voltage, Current BW	0.01, 0.1, 1 kHz
Switching Frequency	10 kHz

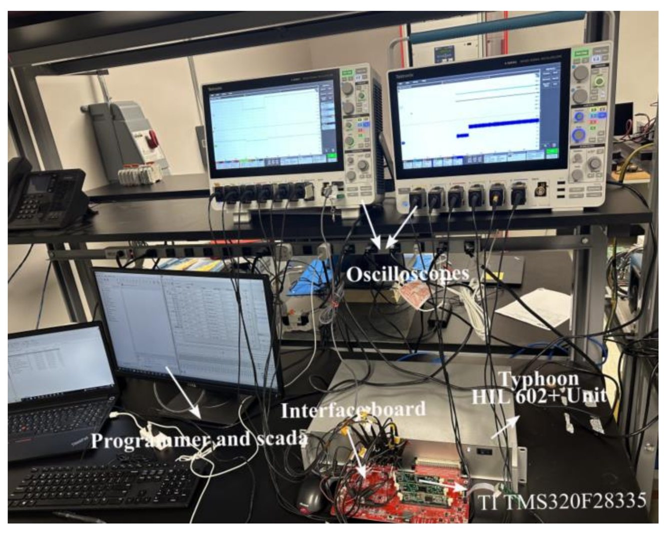

Figure (3) – Typhoon HIL Setup

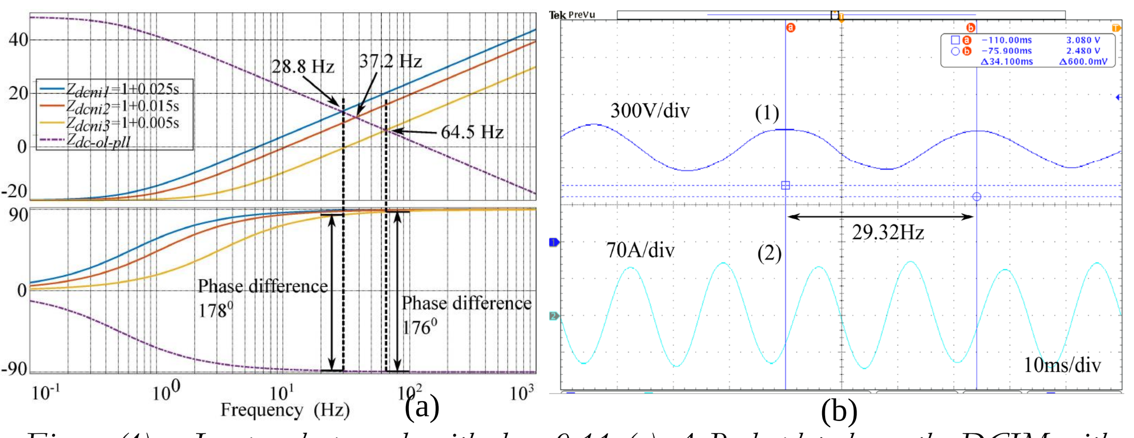

Figure (4) – In open loop mode with d = 0.11 (a) A Bode plot shows the DCIM with various DCNIs, (b) Test result with DCNI: (1) DC link voltage, (2) Grid current

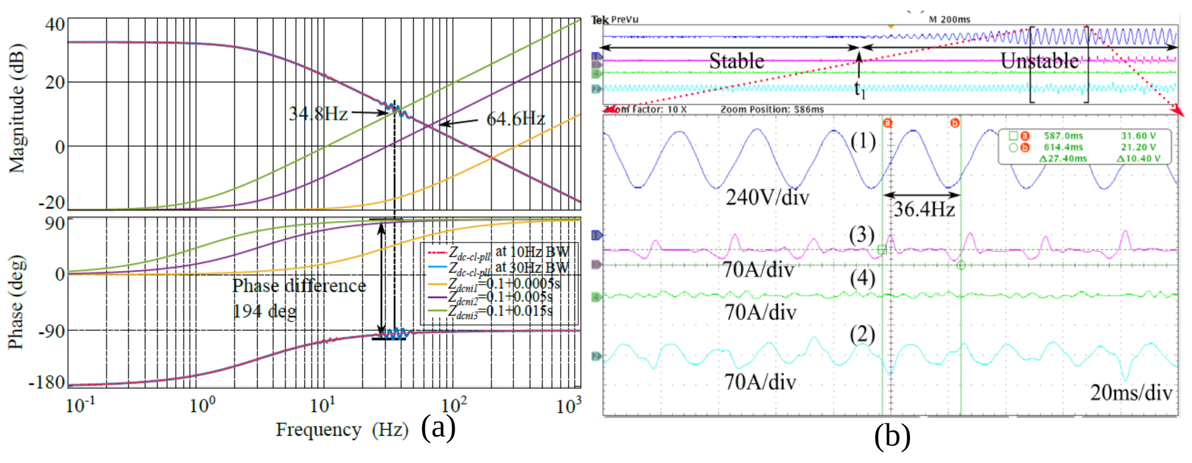

Figure (5) – Closed loop dq current control mode. (a) A Bode plot (b) test result with DCNI: (1) DC link voltage, (2) grid current, (3) d-axis actual current, (4) q-axis actual current.

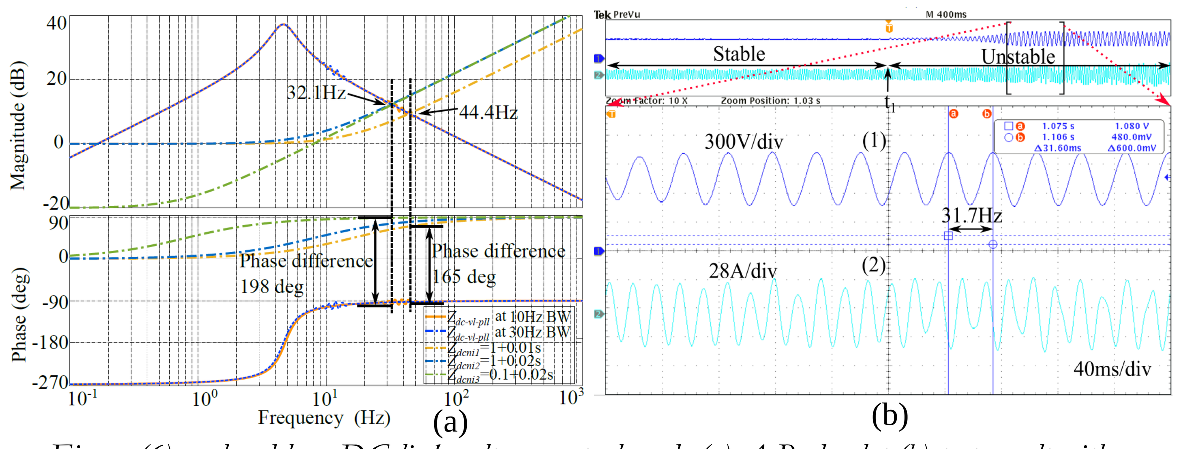

Figure (6) – closed loop DC link voltage control mode (a) A Bode plot (b) test result with DCNI: (1) DC link voltage, (2) grid current.

Conclusions and Future Work

- Small signal DC impedance models are proposed for a grid-integrated BESS system operating in an open loop, closed loop *dq* current control, and DCLV control loop with consideration of PLL dynamics.
- It is verified through bode plots and test results that the interaction between the proposed DCIM and DCNI leads to unstable operation of the closed-loop converter near the PLL bandwidth when the phase difference between DCIM and DCNI is more than 180 degrees.
- The effect of unbalanced grid voltages or faults in the grid-integrated BESS system will be investigated in future tasks.

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