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Aggregated Emulation of Multiple Converters with Heterogeneous Dynamics in Low-Voltage Microgrids – A Clustering Approach

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***Abstract* — The high penetration of renewable generation and the increasing applications of power electronic converters are bringing about stability issues in modern microgrids. Considering multi-dynamic interactions among converters, the system-level modeling and validation of microgrids are of importance, where both the test strategies and hardware implementations are required. In this paper, a clustering method is proposed for stability validation in microgrids based on aggregated emulation of a bus with multi-dynamic converters. The method is demonstrated by real-time simulation results. A reconfigurable test setup is also introduced, which can functionally support the aggregated emulation and also high-fidelity validation of system-level stability in microgrids.**

***Keywords* — Stability analysis, microgrids, model aggregation, power electronic systems, test setup.**

I. INTRODUCTION

Power electronics are the keys to green transition with the increasing penetration of renewable energy in microgrids. However, with more power electronic devices and various controllers, the inertia of microgrids is declining, thereby affecting the reliability of microgrids. The failure of operation may result from both short-term power imbalance between the supply and the demand and long-term accumulative fatigue of components [1]. Under this scenario, the stability and reliability of microgrids are two critical indices, describing the performance of microgrids.

In existing literatures, the stability of microgrids has been extensively studied, including the interaction of converters with grid impedances [2], small-signal stability in multi-converter systems [3], and the stability considering the dynamics of renewable generation (RG) [4]. The modeling is herein playing an efficient role in estimating and predicting the performances of microgrids, and yet the validation is of great significance as well, to ensure the design and operation of microgrids to be convincingly applicable in practice.

Generally, the grid or bus with single first-order dynamics can be regarded as a source with a normally inductive impedance in series. As discussed in [5], the emulation of grid impedance could be a practical approach for the validation, including various power interface techniques and studied bandwidth. Implemented with power electronic converters or power amplifiers, the emulated behavior of the grid can then be conveniently applied to the validation with test facilities of lower economic or energy cost.

However, the validation of microgrids with multiple converters is challenging, which has barely been focused on, especially when considering both the size of system and heterogeneous dynamics of the RG units. With the above, this paper presents a method for stability validation in microgrids based on the model-aggregated emulation of multiple converters. The cluster of converters is then decomposed into a single node or bus with negligible loss of fidelity. By doing so, the modeling and stability validation can be simplified, allowing order reduction in stability studies of microgrids on laboratory testbeds.

Additionally, the control stability is not the only cause of failures in microgrids. The interactions of control loops with different time-scales and multiple converters also contribute to this. Therefore, the capability of higher control bandwidth and system-level coordination will be advantageous in validation. A test setup with a power amplifier and multiple converters is thereby developed. The setup can be employed to perform tests for multi-converter systems with high power capacity and flexibility in reconfiguration, and also provides high-bandwidth possibilities for the aggregated emulation, being practical for the validation of microgrids.

II. AGGREGATED EMULATION OF MICROGRIDS

A. Dynamics of Renewable Generations in Microgrids

In a microgrid like the CIGRE low-voltage (LV) benchmark in Fig. 1 [6], there are multiple converters and RG units with different dynamics. According to [4], the dynamics of the RG units can be described by a first-order inertia. For example, the power of a wind turbine P_{WTG} will change following the wind power P_W with a time delay, expressed in small signal as,

$$G_{WTG}(s) = \frac{K_{WTG}}{1 + sT_{WTG}} = \frac{\Delta P_{WTG}}{\Delta P_W} \tag{1}$$

where K_{WTG} and T_{WTG} is the gain and the time constant, describing the power dynamics.

This also holds for other types of RG units like photovoltaic arrays. The dynamics may include the controller of interface converters as well, but in this paper, the dynamics of RG units are separated from the controllers and simplified as a first-order transfer function concerning the voltage or current reference, which can be expressed as,

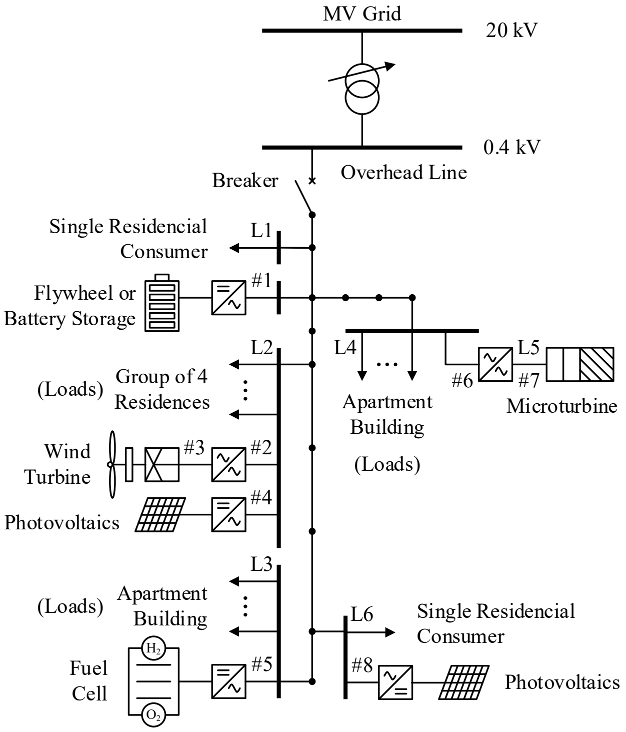


Fig. 1. Configuration of the CIGRE low-voltage (LV) benchmark in [5] with multiple RG units interfaced by power electronic converters.

$$G_{RG}\left(s\right)=\frac{\omega_{RG}}{s+\omega_{RG}}=\frac{V_g^*}{V_{RG}}\ \text{or}\ \frac{I_g^*}{I_{RG}} \tag{2}$$

where ω_{RG} describes the delays of the RG units, V_{RG} and I_{RG} are the voltage (for grid-forming converters) or current (for grid-following converters) estimated from the input power, and V_g^* and I_g^* are the voltage or current reference at the point of common coupling (PCC). It is also known from (2) that the RG units are with the time constant of $\tau_{RG} = 1/\omega_{RG}$.

B. Aggregated Emulation of Multiple Converters

Though there are stability modeling methods for multi-converter microgrids such as [3], it is more complicated to validate microgrids with a larger size or more RG units with different dynamics. Inspired by [7] and [8], when considering microgrids of the system level, it is practical to combine converters with the common AC bus into a cluster for stability study. Compared with [7], emulating the entire cluster, by, e.g., impedances, can further reduce the system size and the validation complexity. For example, the bus with a wind turbine and a photovoltaic array is shown in Fig. 2.

In this case, with all relevant variables defined as Fig. 2, it is possible to derive the voltage drops across the transmission lines as,

$$\begin{cases} v_1 - v_{bus} = i_1 Z_{line1} \\ v_2 - v_{bus} = i_2 Z_{line2} \end{cases} \tag{3}$$

Then,

$$i_{bus} = i_1 + i_2 = \left(\frac{v_1}{Z_{line1}}+\frac{v_2}{Z_{line2}}\right) - v_{bus}\left(\frac{1}{Z_{line1}}+\frac{1}{Z_{line2}}\right) \tag{4}$$

where the bus can be treated as a cluster with the equivalent impedance v_{bus}/i_{bus}.

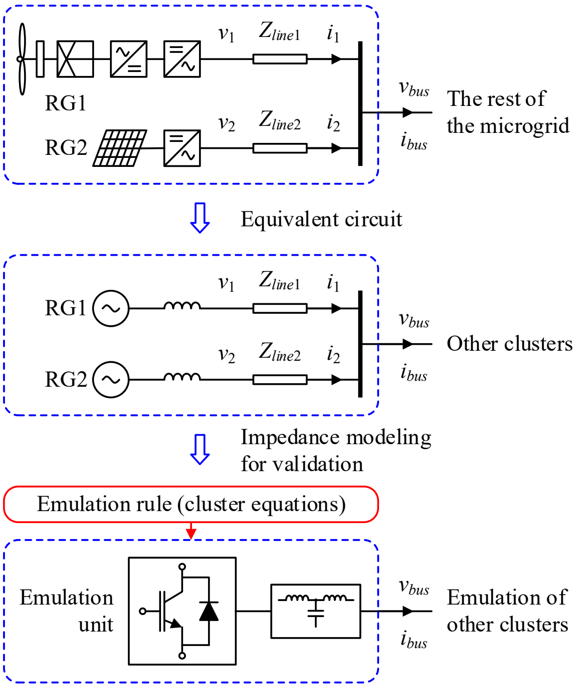


Fig. 2. Aggregated emulation for a multi-converter bus in a microgrid.

If RG units or loads (passive loads, motors, etc.) connected to this bus are considered, v_1 and v_2 may be related to respective control delays or power dynamics,

$$\begin{cases} v_1 = \dfrac{K_1}{1+sT_1}\cdot V_1^* \\ v_2 = \dfrac{K_2}{1+sT_2}\cdot V_2^* \end{cases} \tag{5}$$

where K_1, K_2, T_1, T_2 are the coefficients describing the closed-loop gain or control delays (If the power dynamics are described, the reference can be the rated power instead).

By solving (2) and (3), the behavior of the bus in the system can be determined. The emulation rule revealing the relationship between v_{bus} and i_{bus} can be obtained by, e.g., plotting the amplitudes or phases of v_{bus} and i_{bus} in an X-Y plane, constructing a small-signal state space between v_{bus} and i_{bus}, or derive the transfer function in s-domain between v_{bus} and i_{bus}. The emulation unit in Fig. 2 is programmed according to the emulation rule. In this way, the converters are modeled into a cluster, and the system-level validation of multi-converter microgrids is simplified into a single emulation unit with negligible loss of fidelity.

III. CASE STUDIES AND DISCUSSIONS

To demonstrate the aggregated emulation method, case studies are presented in this section. A bus with two converters connected to the PCC is studied, where the converters operate in either grid-forming or grid-following mode. In this section, the emulation rules are achieved using the s-domain approach, whereas the X-Y plane and small-signal state space can also be employed in practice.

The cases are validated by an OPAL-RT simulation platform. The equivalent cut-off frequency of the dynamics of the two converters are 5 Hz and 2 Hz, respectively. The step size of the real-time simulation is 10 µs, and the model is averaged according to the switching frequency to reduce the burden of computation.

A. Emulation of Grid-Forming Converters

The grid-forming case is exemplified in Fig. 3, where two converters are forming the bus voltage together. It should be noted that this case is presented only for illustrating the emulation rule for grid-forming converters. Thus, the rated voltages and phases of the two converters are set as the same to avoid instability caused by the voltage mismatch at PCC.

Considering that the bus forms the voltage of the microgrid, the emulation unit should act the same. Based on (4) and (5), the relationship is formalized as,

$$v_{bus} = \frac{V_1^* G_1 Z_{line2} + V_2^* G_2 Z_{line1}}{Z_{line1} + Z_{line2}} - i_{bus} \frac{Z_{line1} Z_{line2}}{Z_{line1} + Z_{line2}} \tag{6}$$

where, V_1^* and V_2^* are the voltage references, and G_1 and G_2 are the voltage-forming characteristics of the two converters. Both the dynamics and the closed-loop control are included in G_1 and G_2, and the bus voltage can be thereby obtained according to (6). The emulation scheme is then presented in Fig. 4, where the dynamics are integrated into the emulation unit. The bus voltage is generated through an open-loop modulation scheme, whereas the closed-loop control can also be an alternative solution. It should be noted that the impedance $Z_{line1}Z_{line2}/Z$ is non-causal in s-domain with an underlying differential, which thereby requires approximation in discretization, e.g., using the backward Euler method,

$$s \approx \frac{1 - z^{-1}}{T_s} \Rightarrow s i_{bus} \approx \frac{i_{bus}[n] - i_{bus}[n-1]}{T_s} \tag{7}$$

where T_s is the sampling period, and i_{bus} is the sampled bus current at the PCC.

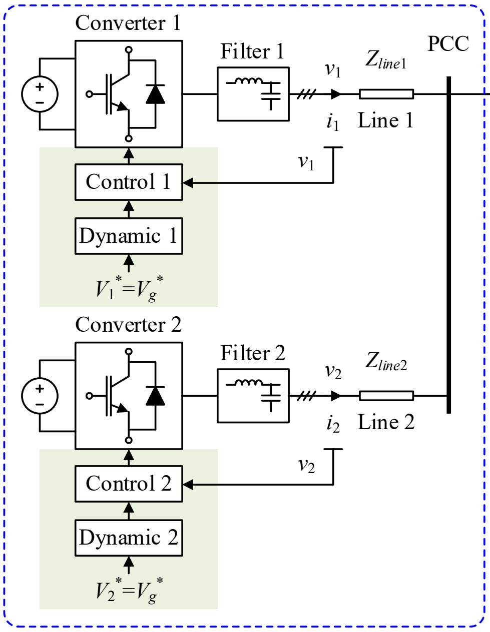


Fig. 3. Example of a grid-forming bus consisting of two converters with different dynamics.

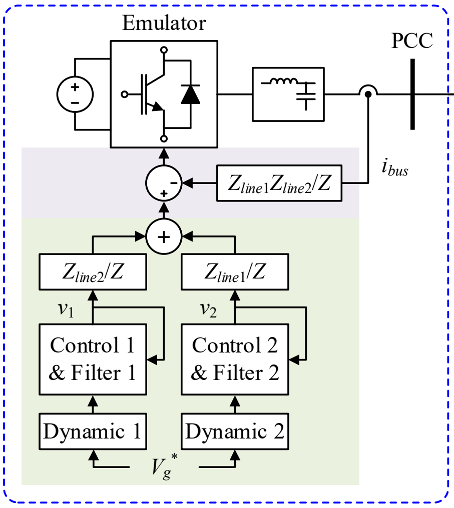
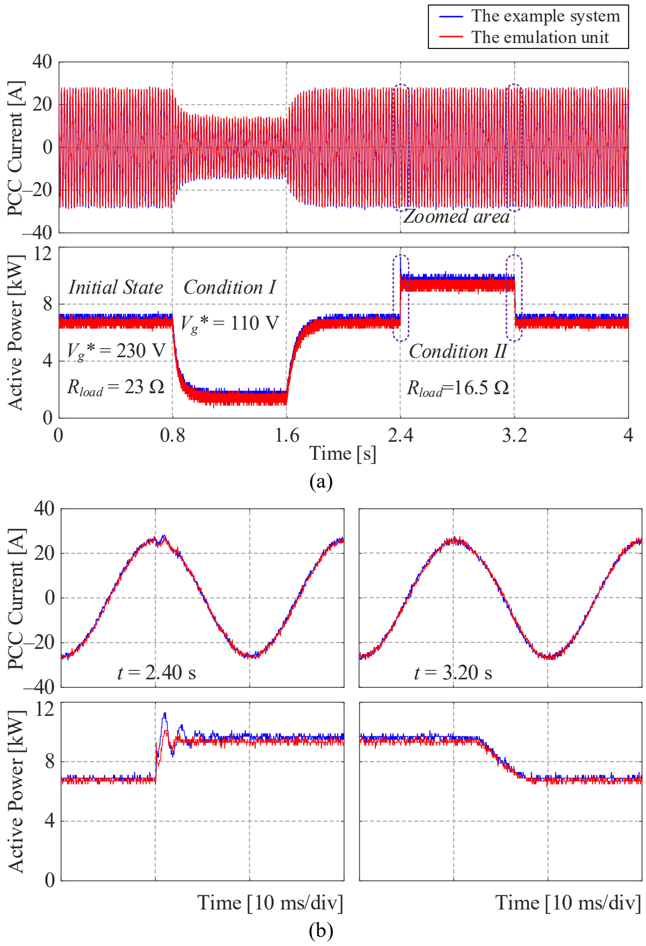


Fig. 4. Emulation scheme of the grid-forming bus in Fig. 3.

The behavior of the aggregated emulation shown in Fig. 4 is compared with that of the example system in Fig. 3, while the comparison results are shown in Fig. 5. Two conditions are considered: In Condition I, the voltage references V_1^* and V_2^* are decreased to 110 V at the same time, and in Condition II, an external load power increase is simulated. In Fig. 5(a), the current at the PCC and the active power can well track that of the example system shown in Fig. 3, indicating that the emulation unit can behave in a similar way to the clustered bus



(a)

(b)

Fig. 5. Performance of the aggregated emulation in the grid-forming case, (a) current at the PCC and the active power transferred to the load, and (b) zoomed view of (a) at $t = 2.40$ s and $t = 3.20$ s.

The dynamic performance of the emulation scheme near $t = 2.40$ s and $t = 3.20$ s is specially shown in Fig. 5(b), where the active power takes a step change. The current waveforms are close to each other, but the powers at $t = 2.40$ s show different overshoots, which could be resulted from the approximation of differentials in (6) or the external *LC* filter in the emulation unit. The filter can bring about another resonant frequency when studying the large-signal instability of the microgrid, and the dynamics can be possibly improved by judiciously select the bandwidth of the filter between the switching frequency and the bandwidth of the voltage control loop in the emulated converters.

B. Emulation of Grid-Following Converters

Similarly, the grid-following case is illustrated in Fig. 6, where the two converters are both controlled as current sources. The grid-following case is more common in microgrids, as the RG units are usually responsible for supporting the power supply in microgrids. However, in this case, the bus current degrades into the sum of the branches according to the Kirchhoff's current law, namely,

$$i_{bus} = i_1 + i_2 = I_1^* G_1 + I_2^* G_2 \tag{8}$$

which can be used as the reference for controlling the bus current i_{bus} in the emulation unit.

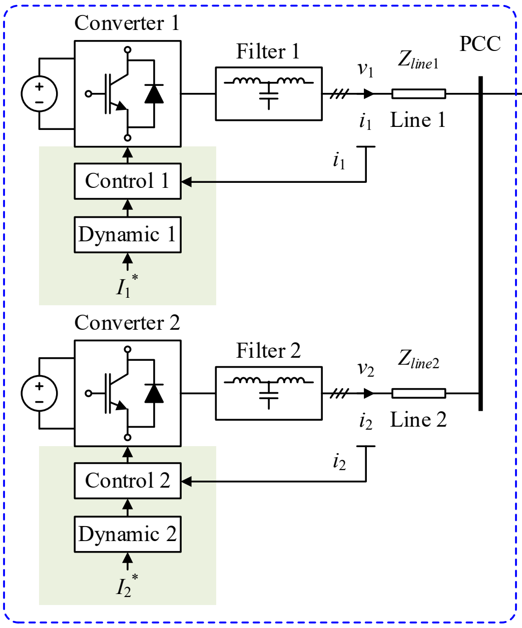


Fig. 6. Example of a grid-following bus consisting of two converters with different dynamics.

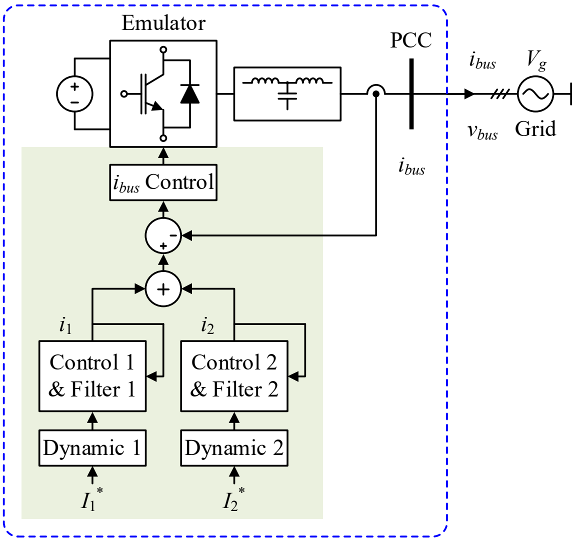


Fig. 7. Emulation scheme of the grid-following bus in Fig. 6.

If further neglecting the current in the capacitor branches of the *LCL* filters (Filters 1 and 2 in Fig. 6), the current control loops will act as a low-pass filter and can be easily implemented by transfer functions. The emulation scheme of the grid-following case is shown in Fig. 7.

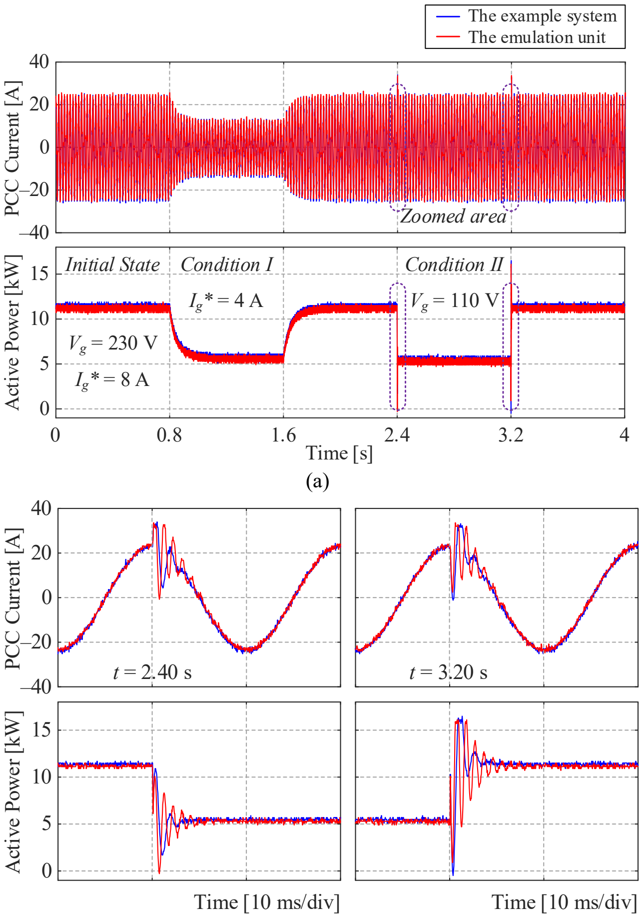
The performance of the emulation unit is shown in Fig. 8. In Fig. 8(a), two conditions are also tested: Condition I where the reference current changes, and Condition II where the grid voltage comes across a sudden drop. The emulated bus current and the active power could follow the change of the emulated bus, also proving the performance of the proposed emulation method.

However, it can be seen from Fig. 8 that this method is actually also limited in high-bandwidth dynamics. Different from the grid-forming case, this is because the control loop for generating the target bus current in the emulation unit works as an extra low-pass filter, which suppresses the high-frequency components. A possible approach is to use a proportional-differential (PD) controller to compensate for the control loop, or using open-loop controllers as similar to [9].

C. Emulation of Hybrid Converters

Similar to grid-forming converters, a bus with both grid-forming and grid-following converters also acts as a voltage source in microgrids. Based on the discussion in Sections III-B and III-C, the equation (3) and (4) should be formed into:

$$v_{bus} = v_1 - \left(i_{bus} - i_2\right) Z_{line1} = V_1^* G_1 - \left(i_{bus} - I_2^* G_2\right) Z_{line1} \tag{9}$$



(a)

(b)

Fig. 8. Performance of the aggregated emulation in the grid-following case: (a) current at the PCC and the active power integrated to the grid, and (b) zoomed view of (a) at $t = 2.40$ s and $t = 3.20$ s.

where Converter 1 is the grid-forming converter. The corresponding emulation scheme is shown in Fig. 9.

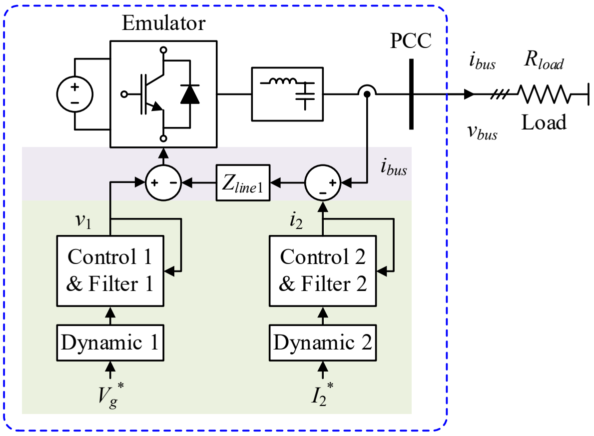


Fig. 9. Emulation scheme of a bus with both grid-following and grid-following converters.

IV. A TEST SETUP FOR THE AGGREGATED EMULATION AND STABILITY VALIDATION

Based on the requirement of validation in a microgrid, a test setup is developed as shown in Fig. 10. High power linear amplifiers (max. 45 kVA) are used as grid simulators, and transformers (max. 40 kVA each) are used for grid-connected tests. Silicon-Carbide (SiC) converters (10 kW per converter) can be controlled in high bandwidth, either as ideal DC-AC converters individually or to emulate the dynamics of RG units or a certain bus. The setup can be flexibly reconfigured with high safety and compatibility, and is thereby well eligible for the aggregated emulation as well as other types of stability validation. The high control bandwidth of the system also enables the emulation to be greatly improved to meet the requirement in fast dynamics like [10].

Due to the limitation of time, relevant experiments are not yet fully performed on this setup, but the results from real-time simulation have proved the feasibility of the schemes. In future studies, the introduced setup will also be used to employ the aggregated emulation of buses so as to perform the comprehensive validation of microgrids.

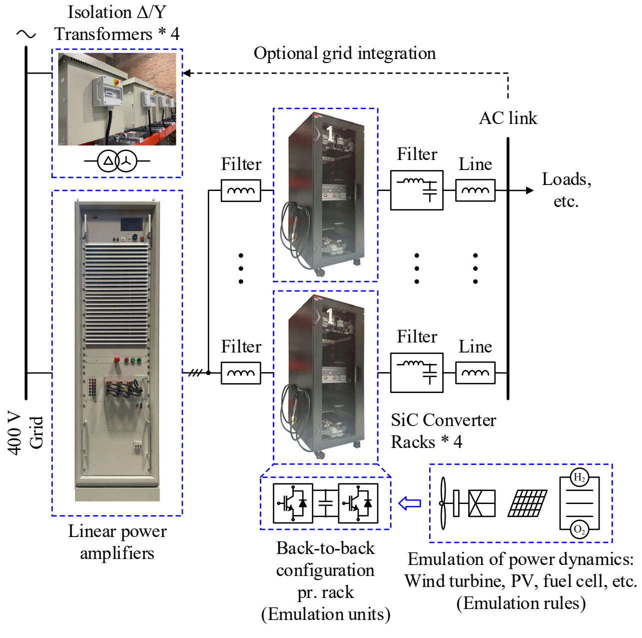


Fig. 10. Example configuration of the setup, which is eligible for the aggregated emulation and stability validation.

V. CONCLUSIONS

In this paper, an aggregated emulation method for the stability validation of multi-converter buses in microgrid is introduced. The emulation can be implemented by an X-Y plot of the input and output, small-signal state spaces, or aggregated transfer functions. The idea is validated by comparisons through typical cases and real-time simulations. By combining multiple converters with heterogeneous dynamics into clusters, the system-level performance of microgrid systems can be validated more efficiently. However, the emulation performances during high-frequency dynamics are still worth being discussed with advanced techniques.

A test setup with high flexibility is also developed accordingly and introduced, which is well eligible for the aggregated emulations as well as other stability validation in microgrids. In the future, the setup will be applied for more tests of microgrids, thus enabling the applications of the proposed idea to function in practice.

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