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System-Level Stability of the CIGRE Low Voltage Benchmark System: Definitions and Extrapolations

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***Abstract* — With the higher penetration of renewable energy and non-linear loads, modern power systems are prone to disturbances due to low inertia and naturally more vulnerable than synchronous-generator-dominated grids. The unstable modes of these systems may vary from disturbances, relevant topologies and multiple time scales in operation. Accordingly, identification of the unstable modes is of importance to formalize guidelines for stability-oriented design of power-electronic-based power systems (PEPS), and to validate the performance of PEPS. In this paper, the CIGRE Low Voltage (LV) benchmark system, which is an exemplary model for up-to-date topics on microgrids, is studied to explore the unstable modes of a microgrid. The performances of the CIGRE LV benchmark system are explored based on the classification of stability, and the unstable modes are identified according to respective root causes, features and consequences. Simulations and experiments based on the CIGRE LV benchmark system are also demonstrated and conclusions are thereby drawn.**

Keywords — stability analysis, unstable modes, microgrids, CIGRE Low Voltage (LV) benchmark

I. Introduction

The stability of a system is defined based on the disturbances imposed on it [1]. Different from conventional power grids with large inertia and high capacity, microgrids are power-electronic-dominated grids with low inertia and low generation capacity, which consequently become prone to disturbances [2]. Considering disturbances with distinct magnitudes, time scales and coupling effect on relevant components, the resultant instability may have different impacts on the performances of microgrids, such as influence on power quality, load shedding or even shutdown of the entire system.

Nevertheless, the stability of microgrids or power-electronic-based power systems (PEPS) can be classified based on causes [1], [3], e.g., control system stability and power imbalance stability. Certain general measures for enhancing microgrid stability have also been provided to guide the operation of microgrids. A more focused example is [4], where the mechanism of grid-synchronization stability related to grid-connected converters is discussed. The roles of controller design, including parameter tuning, active damping and adjustment of power control, are also addressed in it.

However, these discussions are in a general sense, which means limited solutions for a specific system with multiple factors, and an explanatory inspection of instability for modern microgrids with more power electronics and interactions among converters is still needed. Identifying the unstable modes of a microgrid in terms of mechanisms and consequences, is beneficial to the design and performance validation of microgrids.

On the other hand, the CIGRE Low-Voltage (LV) benchmark system [5], has been widely used to evaluate the performance of modern microgrids. The stability issues can be quite common in PEPS, including not only controller-based instability, but also the instability associated with the multiple renewable energy with different dynamics and the interactions among them, which has been overlooked so far.

Therefore, this paper is focusing on identifying the local unstable modes in the CIGRE LV benchmark system and its reflections on the system level. System-level instability is triggered by local disturbances under certain conditions, and these cases are illustrated by simulations and experiments. These unstable modes are also characterized to form a comprehensive and systematic view of the instability in the CIGRE LV benchmark system and in general microgrids.

II. CIGRE Low Voltage Benchmark System and Stability Classification

The CIGRE LV benchmark system is shown in Fig. 1 [5], which is a 400-V distribution system. The system consists of renewable generation systems, energy storage, residential loads and a microturbine as a generator or a rotational load. It can be operating either in islanded or grid-connected mode. Therefore, it is commonly used to validate the performances of modern microgrids.

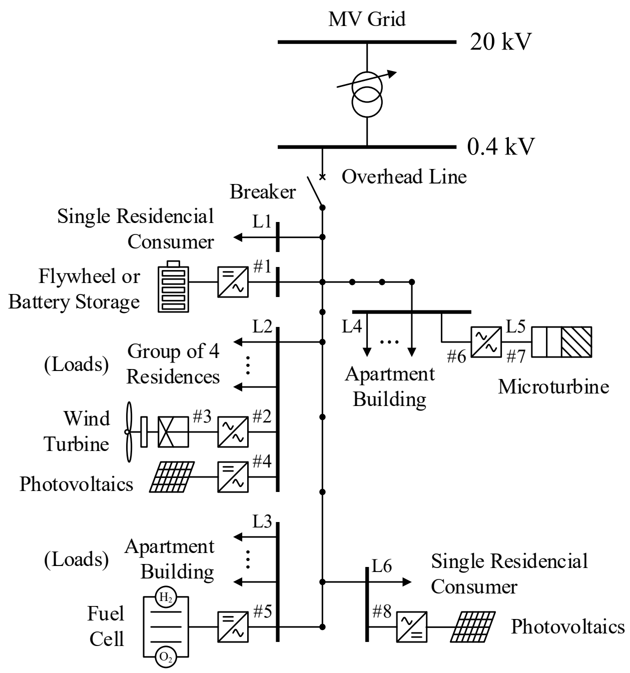


Fig. 1. Schematic of the CIGRE LV benchmark system in [5], where the converters are also marked with respective index "#".

In this paper, the stability in the CIGRE LV benchmark system is studied according to the classifications in [1] and as listed in Fig. 2. The unstable modes will be identified and discussed accordingly: with respect to control system, power supply and the behaviors of renewable generations with multiple time constants.

To simplify the study, only part of the system is considered for each study case. The corresponding components (converters) of each case are also specified in Fig. 2. The instability is triggered in each case under specific conditions.

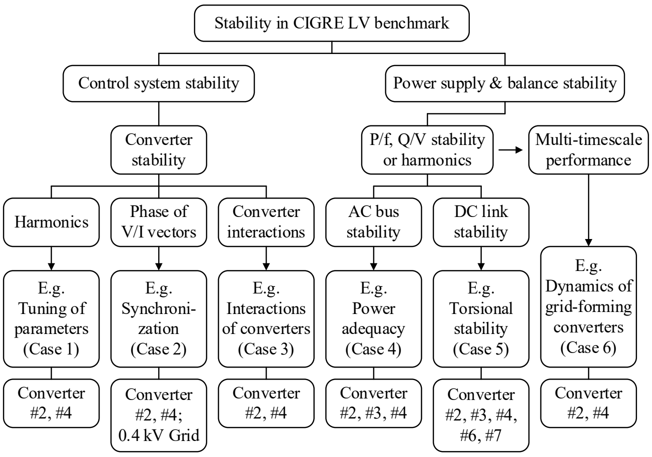


Fig. 2. Classification of stability in the CIGRE LV benchmark system, where corresponding study cases of instability, and relevant converters according to Fig. 1 are also specified.

Remark: *The electric machine stability in* [1] *is basically due to the oscillations of synchronous generators. The electric machine in the CIGRE LV benchmark system is a rotational load driven by back-to-back converters, thus the torsional stability in this paper is classified into DC link stability in terms of active power supply.*

Additionally, the relevant converters (except for back-to-back converters) in each case are assumed to be controlled by droop controllers, and the voltage is controlled with a double-loop scheme as shown in Fig. 3. F is the feedforward gain of the grid-side current of converter, indicating the compensation on transients of the grid-side current.

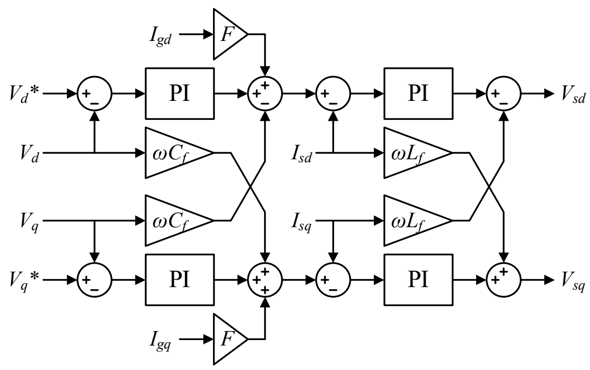


Fig. 3. Double-loop voltage control used in grid-forming converters, where F is the feedforward gain of the grid-side current. The parameters of proportional-integral (PI) controllers are denoted as: K_{pV} and K_{iV} for outer loop, and K_{pC} and K_{iC} for inner loop.

III. Definitions of Unstable Modes in the CIGRE Low Voltage Benchmark System

In this section, the unstable modes in the CIGRE LV benchmark system are studied according to the classification of stability mentioned in Fig. 2. The study is carried out based on PLECS simulations.

A. *Instability from Control System*

Control system stability is normally related to the synchronization of electric machines or the tuning of controllers for converters. Electric machine stability, however, is not so common in microgrids, where machines are normally driven by AC-DC-AC converters in microgrids to enhance the flexibility of operation. In this case, two converters (#2 and #4 in Fig. 1) and a load (L2) at the point of common coupling (PCC) are selected, while the rest part is assumed to be sources (or with reactance), additional *RL* loads or offline. Related transmission lines are also considered.

The modulation of converters is one of the major harmonic sources in microgrids. Instability in the form of resonance due to harmonics can possibly be caused by poor tuning of the controllers, typically voltage controllers [6]. In Fig. 4(a), the proportional gain of the voltage controller K_{pV} (of both converters) is reduced from 0.05 to 0.01, and resonances of voltage and current are consequently appearing, with a harmonic spectrum of current as shown in Fig. 4(b). The resonance can also be modelled by plotting the Bode diagrams of the system. Typically, the resonance frequency is around several hundred to a few thousand Hz. This type of instability might not immediately lead to system failures, but it can be harmful to power quality and can simultaneously increase the stress of power electronic components.

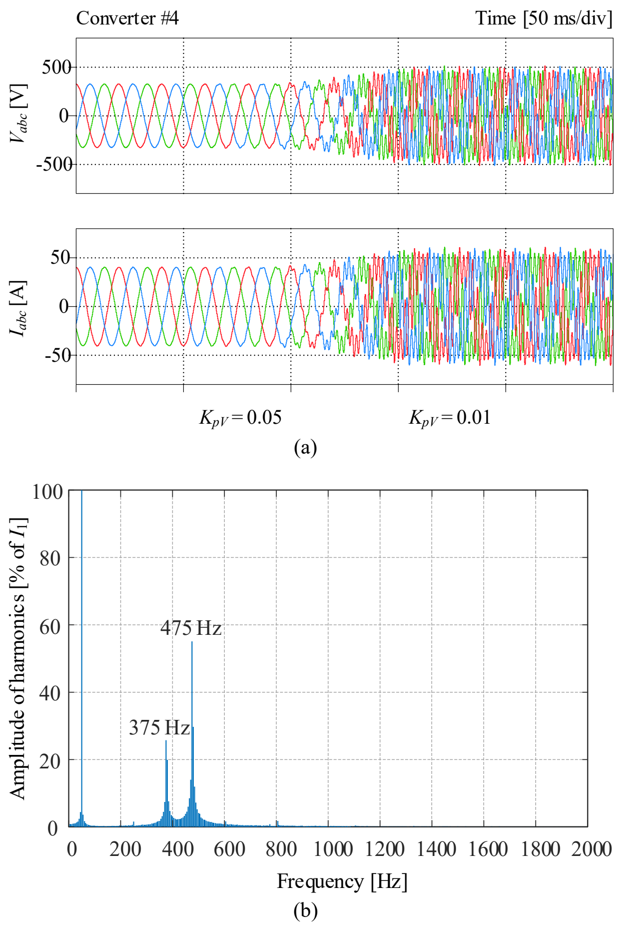


Fig. 4. Instability Case 1 – Tuning of parameters. Resonance triggered by decreasing the parameter of voltage controllers: (a) voltage and current waveforms of Converter #4, and (b) the Fourier analysis (harmonic spectrum)

of current in (a), where I_1 is fundamental component. The major harmonics are around 350 to 500 Hz.

Since many controllers in microgrids are implemented in the $dq0$ frame, the synchronization of converters is also one of the causes of instability. Notably, it is in principle different from the synchronization of synchronous generators. In Fig. 5, droop controllers are used in both Converter #2 and #4. However, when the microgrid is connected to a strong grid with large short-circuit ratio (SCR), the asynchronization at the PCC will lead to instability. To avoid this, grid-following converters with phase-locked loop (PLL) can be used [7], or the decoupling of the two frequencies can be considered (e.g., back-to-back connection via a DC link).

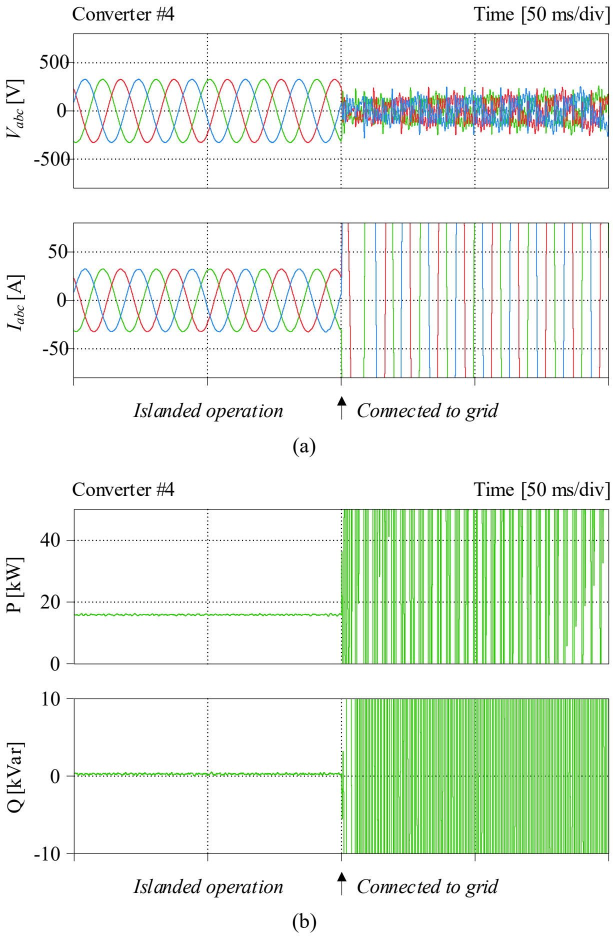


Fig. 5. Instability Case 2 – Synchronization. Instability caused by the loss of synchronization: (a) voltage and current waveforms, and (b) active and reactive power waveforms of Converter #4. The microgrid is connected to an external grid with infinite capacity (a strong grid).

Another control system instability issue comes from the interactions among converters. As mentioned in Fig. 3, the feed-forward of current is always employed in the double-loop control of voltage for improving the dynamic performance [8]. The feedforward gain F is normally between 0 and 1, and the smaller F is, the more strongly the converters are coupled at the PCC. An example is shown in Fig. 6. When the feed-forward gain F is reduced, the coupling of converters will possibly lead to a large magnitude gain and system poles in right-half plane (RHP), and subsequently, an oscillatory behavior between converters can appear. In this case, the amplitude of voltage will first go divergent prior to the frequency, and the time scale will also be larger while the frequency of the power-based oscillation is relatively low (less than fundamental frequency), which can also cause fluctuations of the DC link in AC-DC-AC converters.

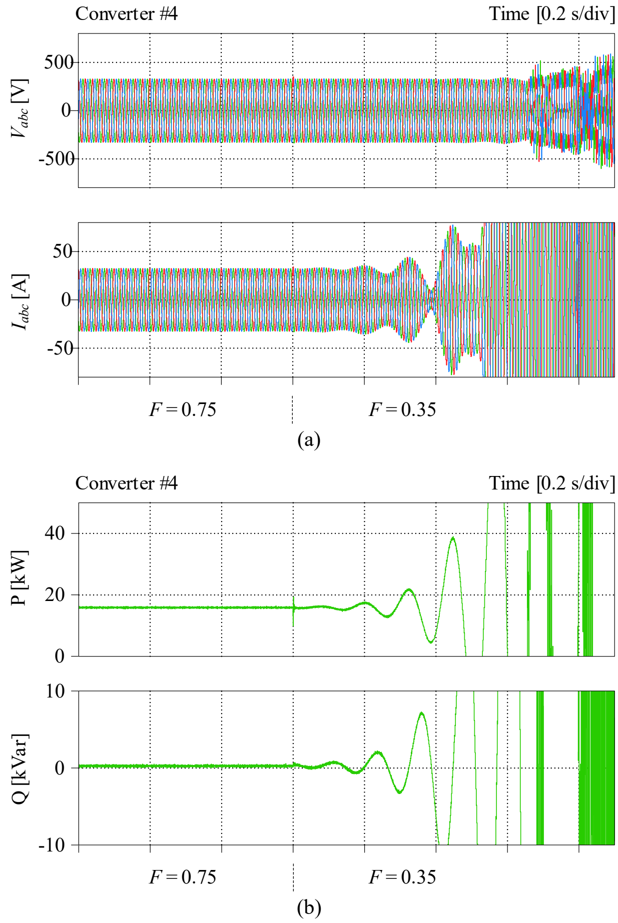
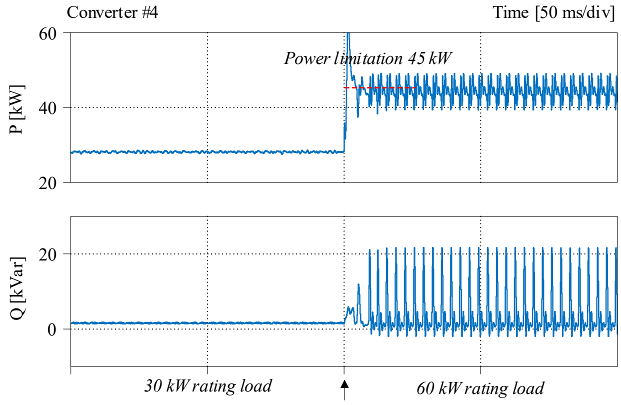


Fig. 6. Instability Case 3 – Interactions of converters. Instability caused by interactions of converters: (a) voltage and current waveforms, and (b) active and reactive waveforms of Converter #4. The feed-forward gain F of current in the double-loop voltage control is reduced.

B. *Instability from Power Supply*

Power supply stability is related to the unbalance of power generation and demand, especially for renewable energy systems. For example, photovoltaic (PV) arrays cannot generate power at night, and wind power cannot change suddenly when the wind speed is constant. If the load increases beyond the capability of power generation, the microgrid system will fail to operate.

In Fig. 7, a permanent magnet synchronous generator (PMSG)-based wind turbine is considered, and the power capacity of Converter #4 is set as 45 kW. When there is a sudden load increase, the power of the wind turbine cannot change accordingly, and the shortage of total power supply occurs. Therefore, the voltage and current are distorted, as shown in Fig. 7(b).



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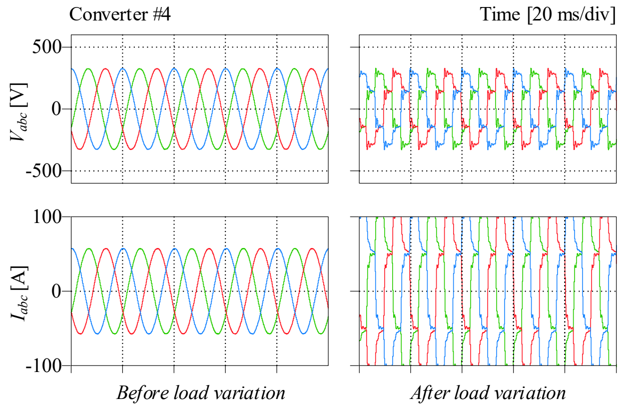
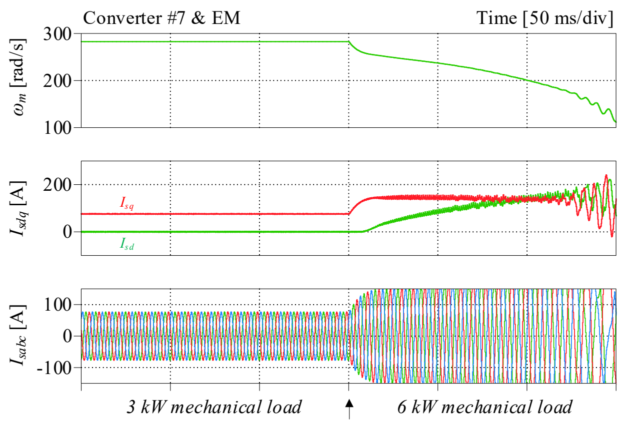


(b)

Fig. 7. Instability Case 4 – Power inadequacy. Instability caused by insufficient power supply: (a) active and reactive power, and (b) voltage and current waveforms of Converter #4 before/after the load variation. The load is increased from 30 kW to 60 kW rating. The maximum power of the source connected to Converter #4 is set as 45 kW.

Another consideration in the power supply is the DC link stability when there are back-to-back converters in microgrids. An example is shown in Fig. 8. The microturbine connected to Converter #7 is considered as a rotational load here, while the rest part is the same as before, including a PMSG and Converter #4 with limited capacity.



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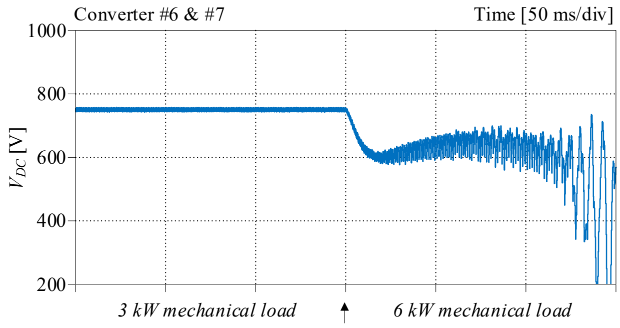

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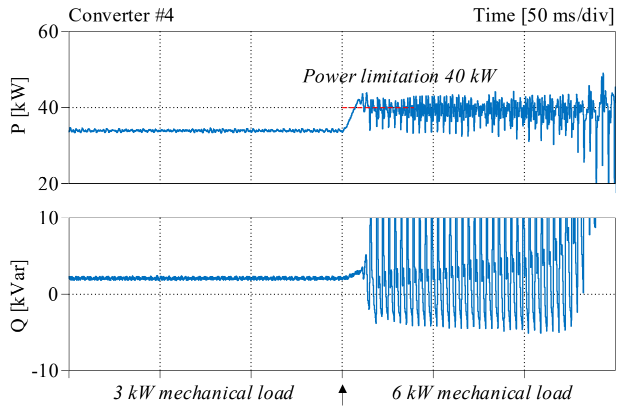


(c)

Fig. 8. Instability Case 5 – Torsional and DC-link instability. Instability caused by insufficient power supply: (a) rotational speed and stator current (in dq and abc frame) of the electric machine, and (b) DC link voltage between Converter #6 and #7, and (c) active and reactive power of Converter #4 before/after the variation of load. The mechanical load is increased from 3 kW rating to 6 kW rating. The maximum power of the source connected with Converter #4 is set as 40 kW.

When the mechanical load increases from 3 kW to 6 kW, there is a voltage drop in the DC link of Converter #6 and #7. Subsequently, the load torque will drag the electric machine into inverse direction, also leading to torsional instability. Unlike the previous case, when the speed of the electric machine is out of control, the system will go into divergence instead of steady harmonics.

C. *Instability from Multiple Time Constants*

Additionally, the multiple time constants in microgrids can also be one of the problems [9]. Such problems can be the interactions of different dynamics between two sources or between a source and a load. When there is a load transient, the renewable generation will show different dynamics (overshoots, adjusting process and adjusting time, etc.). For example, the dynamic of fuel cells is normally much slower than PV and batteries. The difference in dynamics can possibly lead to large-signal instability related to power balance or low-frequency harmonics. Similarly, the renewable generation might not be able to track the power change of specific loads, which is also harmful to system-level stability.

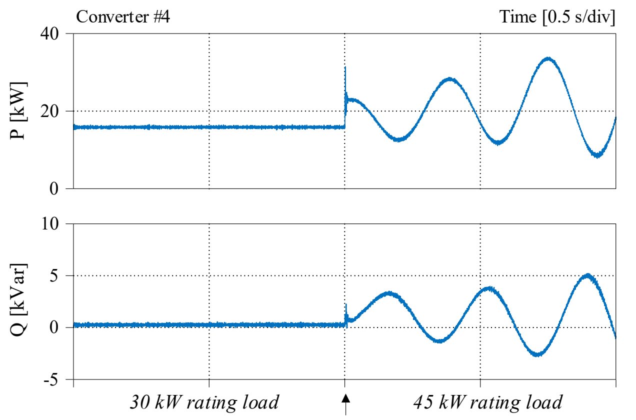


Fig. 9. Instability Case 6 – Dynamics of grid-forming converters. Instability caused by multiple and slow dynamics of grid-forming converters: the active and reactive power of Converter #4 before/after the variation of load. The load is increased from 30 kW to 45 kW rating. The additional delay of Converter #4 is 3% of fundamental frequency, while that of the Converter #2 is 1/10 of Converter #4.

A case is shown in Fig. 9, where the time constants of power in grid-forming converters (in droop control) are set as 3% and 0.3% of the fundamental frequency. The system shows a steady state at the beginning, but the state is quite delicate. When there is a large-signal disturbance of load increase, the system starts to diverge. The power oscillation frequency is 2.74 Hz (0.365 s observed from Fig. 9), and thus, the oscillation of voltage and current is 1.37 Hz, which is approximately the difference between the two characteristic frequencies (3% and 0.3% of 50 Hz). When there are disturbances or transients in a microgrid with multi-timescale sources, low-frequency oscillations could also occur in this pattern.

Comparing the result with the discussions in [10], it can also be concluded that, in power-electronic-based power systems, there should be at least one source or grid-forming converter, with sufficiently fast dynamics and sufficient power capacity.

D. *Summary of the Unstable Modes and Extrapolations*

In general, the unstable modes, their impact and some possible countermeasures are summarized in Table I, with three major types of unstable modes.

TABLE I. SUMMARY OF THE UNSTABLE MODES, SYSTEM IMPACT AND CORRESPONDING COUNTERMEASURES TO AVOID INSTABILITY

Unstable Modes	System Impact	Countermeasures
Control system instability	Harmonics, frequency or voltage divergence	Proper design and system-level verification of control parameters
Power instability	Load shedding, DC link failure or torsional instability	Ensuring sufficient power supply and margin of power capacity
Multi-timescale instability	Improper load sharing or low-frequency harmonics	Proper plan of renewable generations (sizing and time-scale coordination; verification of grid-forming dynamics

IV. EXPERIMENTAL DEMONSTRATIONS OF INSTABILITY

In order to illustrate the unstable modes practically, experiments are also performed. Part of the CIGRE LV benchmark system (Converter #2 and #4) is selected and implemented based on *Imperix*© setup. As shown in Fig. 10, the two converters are in parallel and connected to a resistive load at the PCC. The subsystem is downscaled to match the hardware, but the converters are also controlled by droop controllers, as in the case of simulations.

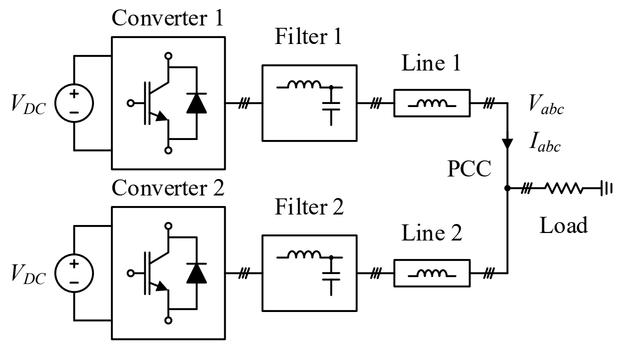
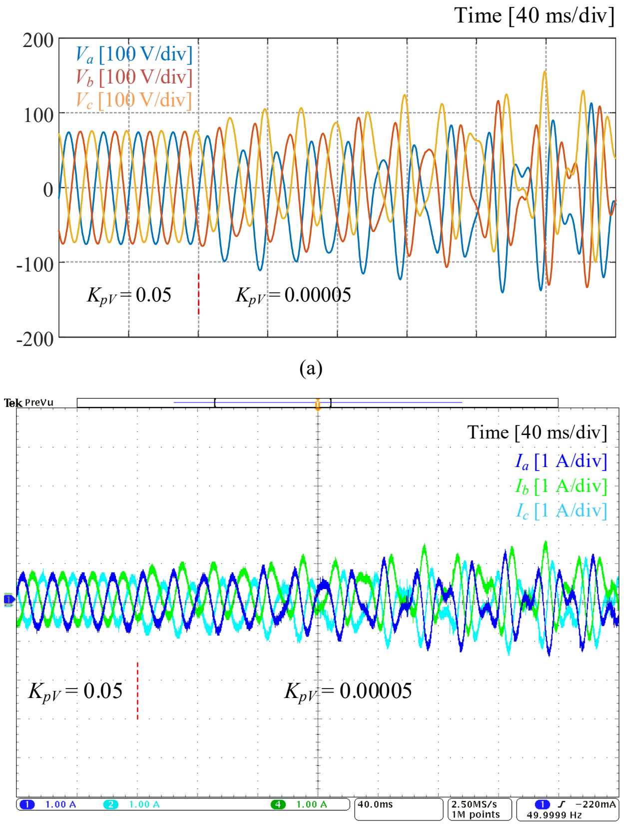


Fig. 10. Topology of the experimental setup. Two converters are in parallel and connected to a resistive load at the PCC.

A. *Demonstration of Instability with Harmonics*

The instability in Case 1 (according to Fig. 2) is first demonstrated by experiments. The voltage and current waveforms are shown in Fig. 11. In the experiments, there exist more components of harmonics than simulations. And the power quality is distorted, though the system does not collapse immediately.

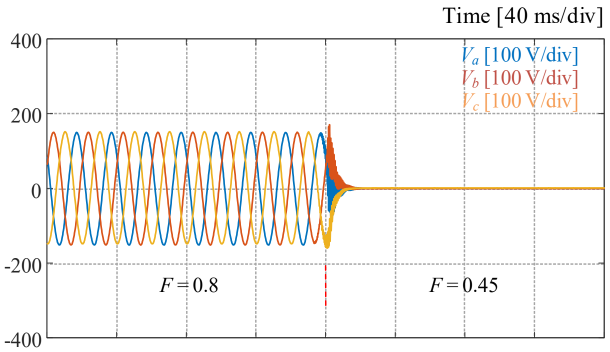


(b)

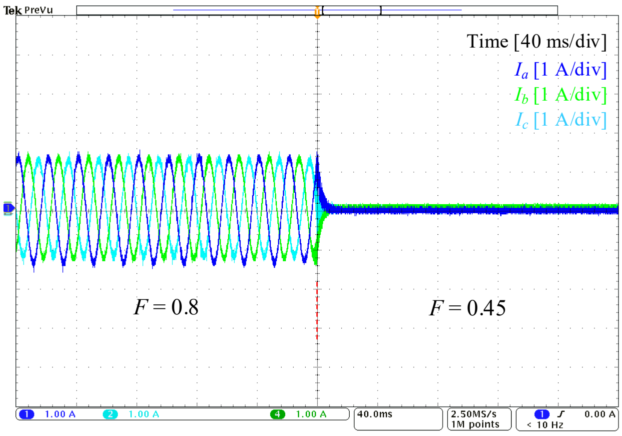
Fig. 11. Experimental results for Case 1 – Tuning of parameters: (a) voltage waveforms (obtained by the sensors of *Imperix*) and (b) current waveforms of the configuration in Fig. 10. The proportional gain of voltage controller K_{pV} is reduced, and the harmonics occur accordingly.

B. *Demonstration of Interactions of Converters*

Experiments on Case 3 are also conducted. In Fig. 12, the feedforward gain F of the current is reduced. However, in the experiments, the oscillation of the voltage is not observed clearly, which is possibly related to the difference of parameters between simulations and experimental tests. The divergence of the system ends up with the action of hardware protection, but the results actually show the impact of interactions among converters and the importance of the feedforward gain F for decoupling.



(a)



(b)

Fig. 12. Experimental results for Case 3 – Interactions of converters: (a) voltage waveforms (obtained by the sensors of *Imperix*) and (b) current waveforms of the configuration in Fig. 10. The feedforward gain F is decreased, which leads to the activation of hardware protection and a sudden shutdown of the setup.

V. Conclusions

In this paper, typical unstable modes of the CIGRE LV benchmark system are illustrated and discussed, showing the causes and the consequences of each mode. The instability can be related to controller parameters, synchronization, interactions of converters, power supply and multi-timescale interactions, which have been demonstrated by simulations and experimental tests. This discussion can be accordingly generalized and utilized, in order to inspect possible instability issues in microgrids and to guide for design and validations of microgrid performances.

Acknowledgment

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