Coupling-Related Instability Mechanism and Mitigation Analysis of the Instantaneous Power Based Current Controlled Inverter

YANXUE YU (Member, IEEE), HUIMIN MA (Member, IEEE), XUEMEI ZHENG, HAOYU LI (Member, IEEE), AND JINGHANG LU (Member, IEEE)

1School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150001, China
2School of Mechanical Engineering and Automation, Harbin Institute of Technology (Shenzhen), Shenzhen 518000, China

Corresponding author: Haoyu Li (lihy@hit.edu.cn)

This work was supported by the State Grid Heilongjiang Electric Power Company Ltd., through “Research on the Influence of High Penetration of Distributed Energy on the Stability of Terminal Power Grid and Its Suppression Method,” under Grant 52243718000T.

ABSTRACT Instabilities related to sequence-couplings of current controlled inverters (CCIs) have been recognized recently, but limited to accurate stability analysis of CCIs synchronized to the grid by the phase-locked loop (PLL). As for CCIs, another feasible grid-synchronization method is based on the instantaneous power (IP) theory, while instability recognitions of the IP-based CCI (IP-CCI) are lacking. Therefore, this paper reveals the instability mechanism and mitigation of the IP-CCI by comparison with the PLL-based CCI (PLL-CCI). Specifically, sequence-admittances of the IP-CCI are modeled, and interactions between sequence-couplings and circuit-coupling of the CCI-grid system are analyzed further. Simultaneously, influences of different system parameters on instabilities of the IP-CCI are thoroughly studied. Studies indicate that sequence-admittances of the IP-CCI exhibit closer sequence-couplings in comparison to that of the PLL-CCI, and negative damping of the IP-CCI is resulted from sequence-couplings, which clarifies interactive instabilities of the grid-connected IP-CCI are coupling-related. Therefore, corresponding instability mitigation can be achieved via sequence-decoupling methods, like the studied controller parameters regulation methods and the filter-based methods. Whereas, the stability deterioration level of sequence-couplings is grid-impedance-dependent, which means the weak grid would limit the decoupling performance. Nyquist plots, simulations and experiments are carried out to verify the studied coupling-related instability of the IP-CCI.

INDEX TERMS Current controlled inverter, instantaneous power, sequence-admittance, coupling-related instability.

I. INTRODUCTION

The three-phase voltage source inverter (VSI) has been widely used in the evolving distributed generation systems because of its flexible control features [1]–[3]. Due to the nonnegligible grid impedance, when the VSI is connected to the power grid, circuit-couplings of the VSI and grid would bring some resonant points into the system. If the system exhibits negative damping (ND) at the resonant frequencies, the system cannot run stably [4], [5]. Generally, most small-signal instability is related to the current-controlled inverters (CCIs) [6]–[8]. For the interconnected CCI-grid system, the grid features are varied in different environments, i.e., the power grid shows weak grid characteristics in some remote areas [5], the power grid may contain the capacitive grid impedance due to the existing single-phase motor-driven loads or the power factor correction capacitors [9]. It is difficult to change the grid environment for the CCI, but it is possible to optimize the control of the CCI or adopt some damping strategies to ensure the stability of the CCI-grid system. Therefore, it is significant to study the instability characteristics of the CCI, thus recognize the control schemes that can ensure the stability between the inverter and the grid.

Corresponding instability studies are focused on the CCIs synchronized to the grid by the phase-locked loop (PLL) [3], [6]–[8], which is named as PLL-CCI in this
paper. The locked phase is used for the Park transformations, which not only increases the complexity but could bring in some resonances to the VSI. Therefore, researchers have explored the use of proportional-resonant controller instead of the proportional-integral controller under the stationary-reference-frame (SRF) to avoid the Park transformation [10], [11]. For the SRF-controlled CCIs, besides the PLL, the inverters can also achieve synchronization with the grid through the instantaneous power (IP) theory as written in (1). In (1), \( P_r \) and \( Q_r \) are the given active and reactive power (If the output power \( P_e \) and \( Q_e \) track the references well, it is valid that \( P_r = 1.5P_e \) and \( Q_r = 1.5Q_e \); \( v_\alpha \) and \( v_\beta \) are the sampled three-phase voltages transformed into SRF; \( i_{\alpha r} \) and \( i_{\beta r} \) are the synchronized current references for the inner current control loops. Recently, vector current control without the PLL under stationary-rotating-reference-frame (SRRF), deduced also based on the IP theory, has been proposed in [12]. For the IP-based CCIs (IP-CCIs) achieved in SRF or SRRF, Park transformations can be omitted. In this condition, the PLL-induced instabilities in low-frequency range would no longer exist in theory. In other words, the IP-CCI could get rid of the low-frequency instability problems related to the PLL. However, researches in [12] have pointed out that a band pass filter is needed to eliminate the harmonic instability of the IP-CCI, whose instability issues have not been revealed. Therefore, to recognize performances of the IP-CCI clearly, it is necessary to research its instability and damping features besides its well-recognized dynamical response.

\[
\begin{bmatrix}
    i_{\alpha r} \\
    i_{\beta r}
\end{bmatrix}
= \begin{bmatrix}
    \frac{1}{v_\alpha^2 + v_\beta^2} & v_\beta \\
    v_\alpha & -v_\beta
\end{bmatrix}
\begin{bmatrix}
    P_r \\
    Q_r
\end{bmatrix}
\]  

A widely used stability analysis model of the grid-connected CCI is based on the admittance-ratio (or impedance-ratio) [13], represented by the dq-domain admittance-ratio and sequence-domain admittance-ratio [14], [15]. Researches have pointed out that both of dq-domain admittances and sequence-domain admittances show coupling features [16]. The former is due to the coupled d- and q-channel control, whose coupling characteristics are familiar to researchers. While studies on couplings in sequence-domain are carried out recently [16]–[22]. The early stability analysis by sequence-domain admittance is based on the single-input and single-output (SISO) positive- and negative-sequence admittance [6]. Until 2016, [16] pointed out the sequence-couplings and modeled the full sequence-admittance matrix of PLL-CCI. The stability analysis results indicated that ignoring the small coupling terms would lead to a wrong estimation of the system stability. Then, [17] proposed a more detailed harmonic transfer matrix to model the frequency-coupling and sequence-coupling. Additionally, sequence-couplings in single-phase grid-connected CCI have also been proposed in [18] and [19], where the coupling effect of the PLL is expressed by the multi-frequency impedance matrix. Furthermore, considering sequence-couplings, many studies have tried to convert the admittance or impedance matrix to its equivalent SISO models to simplify the stability analysis [20]–[23]. Representatively, [20] derived the equivalent sequence-impedance models in the disturbing frequency and coupling-induced frequency directly. Reference [21] tried to convert the multi-input and multi-output (MIMO) dq-domain impedance-based stability analysis model into its equivalent SISO sequence-domain models, and [22] revealed the relationships of the dq-domain impedance and modified sequence-domain impedance. Additionally, stability analysis of single-phase CCIs in [18] and [19] replaced the multi-frequency impedance matrix by modified single-frequency impedance. Thus, the PLL-related resonances in single-phase CCI were clarified and mitigated. However, most stability analysis in sequence-domain is carried out by means of Nyquist plots, which fail to express the resonance deterioration and mitigation mechanism under varied control parameters. Comparatively, the Bode plots can describe clear terminal behaviors of the grid-connected CCI [23], like the damping features and resonant points.

In view of the above considerations, by means of the sequence-admittance models plotted in Bode diagrams, this paper will recognize the coupling-related instability mechanism and mitigation of the IP-CCI by comparison with the PLL-CCI. Accordingly, sequence-admittance models of the IP-CCI are derived firstly, and corresponding admittance characteristics are analyzed in Section II. Additionally, considering that the existing instability studies towards sequence-couplings are limited to accurate stability evaluation, this paper re-analyzes the coupling-related instability from the damping characteristics. Therefore, influences of the sequence-couplings on the inverter-grid interactive stability are analyzed and the coupling-related ND are revealed in Section III. Furthermore, Section IV presents influences of different system parameters on the coupling-related instability of the IP-CCI comprehensively. Specifically, controller regulation methods and filter-based methods that achieving sequence-decoupling in different frequency range are analyzed. In Section V, the new instability recognition and analysis of the IP-CCI are validated via the Nyquist curves, time-domain simulation and 5-kW-inverter experimental platform. Finally, Section VI concludes this paper.

II. SEQUENCE-ADMITTANCE MODELING, VERIFICATION AND ANALYSIS OF THE IP-CCI

A. SEQUENCE-ADMITTANCE MODELING

Fig. 1 shows the topology and control scheme of the studied IP-CCI [11]. Where, \( V_{dc} \) is the dc-side voltage, which is considered constant here; \( u_{k e}, u_{k a} \) and \( v_k \) represent the output voltage of the three-phase bridge, the voltage across the capacitance branch and the voltage at the point of common coupling (PCC), respectively; \( R_1 \) is the damping resistance added to the \( L_1-C_1-L_2 \) filter; \( i_k \) represents the controlled grid-side current; the grid is represented by the voltage source \( v_{g k} \) in series with the line inductance \( L_g \). In the control loop,
The voltage and current sampling transfer functions; \(i_a\) and \(i_b\) are the sampled three-phase currents transformed into SRF; \(H_n(s)\) is the proportional-resonant current controller described as (2), where \(K_p\) and \(K_s\) denote the proportional and resonant coefficients, respectively; \(m_a\) and \(m_b\) denote the outputs of the current controllers; \(m_k\) represents the modulation wave of the SPWM; \(u_{ok}\) is the switch signal. The subscript \(k\) denotes phase A, phase B and phase C, where \(k = a, b, c\). Additionally, \(Q_r\) is set to zero to ensure the unity power factor.

\[
H_n(s) = K_p\left(1 + \frac{K_s s}{s^2 + \omega_0^2}\right) \tag{2}
\]

The sequence-admittances will be derived according to the harmonic linearization method. Take the phase A voltage as an example, after superimposing small-signal perturbations, it can be written as:

\[
v_a(t) = V_1 \cos(2\pi f_1 t) + V_p \cos(2\pi f_p t + \varphi_p) + V_n \cos(2\pi f_n t + \varphi_n) \tag{3}
\]

where \(V_1\) and \(f_1\) are the amplitude and frequency of the fundamental voltage; \(V_p\) and \(f_p\) and \(\varphi_p\) are the amplitude, frequency and phase of the positive-sequence voltage perturbation; \(V_n\), \(f_n\) and \(\varphi_n\) are the amplitude, frequency and phase of the negative-sequence voltage perturbation. Describe them in frequency-domain, \(V_a\) can be written as follows:

\[
V_a[f] = \begin{cases} 
V_1, & f = \pm f_1 \\
V_p, & f = \pm f_p \\
V_n, & f = \pm f_n 
\end{cases} \tag{4}
\]

where \(V_1 = \sqrt{2}V_1\), \(V_p = \sqrt{2}V_p\) and \(V_n = \sqrt{2}V_n\). This paper, the bold capital letters represent the frequency-domain descriptions, including the amplitude, the phase and the frequency information of the signal. Other two phases can be described similarly as (3) and (4). After Clark transformation, the sampled voltages are described as (5), where \(s = j2\pi f\).

\[
V_a[f] = \begin{cases} 
\pm jV_1 G_1(s), & f = \pm f_1 \\
\pm jV_p G_p(s), & f = \pm f_p \\
\pm jV_n G_n(s), & f = \pm f_n 
\end{cases} \tag{5}
\]

According to the convolution theorem, we can derive:

\[
\begin{align*}
V_a^2 + V_b^2 &\] \tag{6}
\[
V_p^2 G_r(s), & f = \pm f_1 \\
2V_1 G_r(s \pm f_1) & f = \pm (f_p - f_1) \\
2V_1 G_r(s \pm f_1) & f = \pm (f_n + f_1)
\end{cases}
\]

Based on the convolution theorem, substitute (5) and (6) into (1) and neglect small squared terms of the perturbations, the frequency-domain current references are described as:

\[
I_a[f] = \begin{cases} 
\frac{P_r}{2V_1 G_r(s \pm f_1)}, & f = \pm f_1 \\
\frac{-V_p^2 G_r(s \pm 2f_1) + P_r}{V_1 G_r(s \pm 2f_1)}, & f = \pm (f_p - 2f_1) \\
\frac{-V_n^2 G_r(s \pm 2f_1) + P_r}{V_1 G_r(s \pm 2f_1)}, & f = \pm (f_n + 2f_1)
\end{cases} \tag{7}
\]

\[
I_b[f] = \begin{cases} 
\frac{P_r}{2V_1 G_r(s \pm f_1)}, & f = \pm f_1 \\
\frac{-V_p^2 G_r(s \pm 2f_1) + P_r}{V_1 G_r(s \pm 2f_1)}, & f = \pm (f_p - 2f_1) \\
\frac{-V_n^2 G_r(s \pm 2f_1) + P_r}{V_1 G_r(s \pm 2f_1)}, & f = \pm (f_n + 2f_1)
\end{cases} \tag{8}
\]

In (7) and (8), \((f_p - 2f_1)\) and \((f_n + 2f_1)\) are the coupling frequencies in negative-sequence and positive-sequence, respectively. That means the current reference of the IP-CCI just has disturbed signals at the coupling frequencies. Differently, the inner loop current reference of the traditional studied PLL-CCI contains signals mainly at the perturbed frequencies \(f_p\) and \(f_n\), and only small coupling terms observed at \((f_p - 2f_1)\) and \((f_n + 2f_1)\) [16, 17, 21].

Assume that the corresponding phase A current at PCC is described as:

\[
i_a(t) = I_1 \cos(2\pi f_1 t + \varphi_1) + I_p \cos(2\pi f_p t + \varphi_p) + I_m \cos(2\pi f_m t + \varphi_m) \tag{9}
\]

where \(I_1\) and \(\varphi_1\) are the amplitude and phase of the fundamental current response; \(I_p\) and \(\varphi_p\) are the amplitude and phase of the current response at the perturbed positive-sequence frequency \(f_p\); \(I_m\) and \(\varphi_m\) are the amplitude and phase of the current response at the perturbed negative-sequence frequency \(f_n\); \(I_{mp}\) and \(\varphi_{mp}\) are the amplitude and phase of the current response at the coupling negative-sequence frequency \((f_p - 2f_1)\); \(I_{mp}\) and \(\varphi_{mp}\) are the...
amplitude and phase of the current response at the coupling positive-sequence frequency \( (f_n + 2f_1) \). In frequency-domain, \( i_a \) can be written as \( (10) \), where \( I_1 = I_1/2e^{j\phi_1} \), \( I_p = (I_{np}/2)e^{j\phi_{np}} \), \( I_{np} = (I_{np}/2)e^{j\phi_{np}} \), \( I_n = (I_n/2)e^{j\phi_n} \), and \( I_{np} = (I_{np}/2)e^{j\phi_{np}} \).

\[
I_a[f] = \begin{cases} 
I_1, & f = \pm f_1 \\
I_p, & f = \pm f_p \\
I_{np}, & f = \pm (f_p - 2f_1) \\
I_n, & f = \pm f_n \\
I_{np}, & f = \pm (f_n + 2f_1)
\end{cases} \tag{10}
\]

Other two phases can be described similarly as \((9)\) and \((10)\). After Clark transformation, the sampled currents are described as:

\[
I_a[f] = \begin{cases} 
I_1 G_i(s), & f = \pm f_1 \\
I_p G_i(s), & f = \pm f_p \\
I_{np} G_i(s), & f = \pm (f_p - 2f_1) \\
I_n G_i(s), & f = \pm f_n \\
I_{np} G_i(s), & f = \pm (f_n + 2f_1)
\end{cases} \tag{11}
\]

\[
I_{\beta}[f] = \begin{cases} 
\mp I_1 G_i(s), & f = \pm f_1 \\
\mp I_p G_i(s), & f = \pm f_p \\
\mp I_{np} G_i(s), & f = \pm (f_p - 2f_1) \\
\mp I_n G_i(s), & f = \pm f_n \\
\mp I_{np} G_i(s), & f = \pm (f_n + 2f_1)
\end{cases} \tag{12}
\]

According to the control scheme as depicted in Fig. 1, it can be derived that:

\[
[l_{ar}[f] - I_a[f]] \cdot H_n(s) G_d(s) = u_k(s) \tag{13}
\]

where \( G_d(s) = e^{-1.5sT_s} \), denoting the switching period. \( T_s \) represents the switching period.

From the main circuit of the IP-CCI in Fig. 1, the relationship among \( u_k, v_k \) and \( i_k \) can be deduced as follows:

\[
u_k(s) = \left[ L_1 L_2 s^2 \cdot \frac{1}{R_1 + 1/(sC_1)} + (L_1 + L_2)s \right] \cdot i_k(s) + \left[ L_1 s \cdot \frac{1}{R_1 + 1/(sC_1)} + 1 \right] \cdot v_k(s) \tag{14}
\]

For simplicity, define that: \( P_1(s) = L_1 L_2 s^2/[R_1 + 1/(sC_1)] + s \cdot (L_1 + L_2), P_2(s) = L_1 s/[R_1 + 1/(sC_1)] + 1 \).

By substituting \((7), (11) \) and \((14) \) into \((13) \), the positive- and negative-sequence admittances of the IP-CCI can be obtained as follows:

\[
Y_{ip}(s) = -\frac{I_p}{V_p} = \frac{P_2(s)}{P_1(s) + H_n(s) G_i(s) G_d(s)} f = \pm f_p \tag{15}
\]

\[
j_p(s) = -\frac{I_{np}}{V_p} = \frac{P_r}{V_1^2 \cdot G_d^2(\mp \omega_1)} \frac{P_1(s) + H_n(s) G_i(s) G_d(s)} f = \pm (f_p - 2f_1) \tag{16}
\]

\[
j_n(s) = -\frac{I_n}{V_n} = \frac{P_2(s)}{P_1(s) + H_n(s) G_i(s) G_d(s)} f = \pm f_n \tag{17}
\]

\[
J_n^{IP}(s) = \frac{I_{np}}{V_n} = \frac{P_r}{V_1^2 \cdot G_d^2(\mp \omega_1)} \frac{P_1(s) + H_n(s) G_i(s) G_d(s)} f = \pm (f_n + 2f_1) \tag{18}
\]

where \( Y_{ip}(s) \) and \( Y_n^{IP}(s) \) are called the positive-sequence and negative-sequence self-admittances (SAs) of the IP-CCI, respectively; \( j_p^{IP}(s) \) and \( J_n^{IP}(s) \) are the coupled-admittances (CA) of the IP-CCI resulted from the positive-sequence and negative-sequence perturbations, respectively. \( \omega_1 = 2\pi f_1 \).

With respect to the PLL-CCI, corresponding sequence-admittances have been well built \([3, 16]\), which are listed here to understand the instability of the IP-CCI better:

\[
Y_{ip}^{PLL}(s) = \frac{P_2(s) - 0.5I_{dr} F_{PLL}(s \mp 2\omega_1) G_d(s) G_i(s) H_n(s)} \frac{G_d(s) H_n(s) G_i(s) G_d(s) + P_1(s)} f = \pm f_p \tag{19}
\]

\[
j_p^{PLL}(s) = \frac{0.5I_{dr} F_{PLL}(s \pm 2\omega_1) G_d(s) G_i(s) + P_1(s)} \frac{G_d(s) H_n(s) G_i(s) G_d(s) + P_1(s)} f = \pm (f_p - 2f_1) \tag{20}
\]

\[
j_n^{PLL}(s) = \frac{P_2(s) - 0.5I_{dr} F_{PLL}(s \pm 2\omega_1) G_d(s) G_i(s) H_n(s)} \frac{G_d(s) H_n(s) G_i(s) G_d(s) + P_1(s)} f = \pm f_n \tag{24}
\]

\[
j_{np}^{PLL}(s) = \frac{0.5I_{dr} F_{PLL}(s \mp 2\omega_1) G_d(s) G_i(s) + P_1(s)} \frac{G_d(s) H_n(s) G_i(s) G_d(s) + P_1(s)} f = \pm (f_n + 2f_1) \tag{25}
\]

where \( Y_{ip}^{PLL}(s) \) and \( Y_n^{PLL}(s) \) are the positive-sequence and negative-sequence SAs of the PLL-CCI, respectively; \( j_p^{PLL}(s) \) and \( j_n^{PLL}(s) \) are the coupled-admittances (CA) of the PLL-CCI resulted from the positive-sequence and negative-sequence perturbations, respectively. \( I_{dr} \) is the active power current reference. In this paper, the studied CCIs are running with the unity power factor. \( I_{dr} \) and \( P_r \) satisfy that \( P_r = V_1 I_{dr} \). \( F_{PLL}(s) \) represents the transfer function of the PLL, it is described as:

\[
F_{PLL}(s) = \frac{H_{PLL}(s)}{1 + H_{PLL}(s)V_1} \tag{26}
\]

\[
H_{PLL}(s) = \frac{1}{s} \cdot K_p (1 + \frac{K_i}{s}) \tag{27}
\]

**B. SEQUENCE-ADMITTANCE VERIFICATION AND ANALYSIS**

To verify the modeled admittances, a frequency sweep method is applied in PLECS. Corresponding measurement scheme is shown in Fig. 2, where the grid impedance \( Z_g \) is set to zero when verify SAs and CAs. The output voltages of Inverter 1 are perturbed by \( V_p \) and \( V_n \) at different frequencies, respectively. While Inverter 0 is running without any voltage disturbances. Therefore, the voltage perturbation \( \Delta u \) and corresponding current response \( \Delta i \) can be derived by subtracting \( u_0 \) and \( i_0 \) from \( u_1 \) and \( i_1 \), respectively. Then, apply DFT analysis to \( \Delta u \) and \( \Delta i \), the frequency spectrum \( V_p, V_n, I_p, I_0, I_{np} \) and \( I_{np} \) can be acquired. Finally, corresponding sequence-admittances would be obtained by calculating the ratios of currents and voltages.

Table 1 shows the system parameters of the IP-CCI and PLL-CCI equipped with the same current controller.
Additionally, the ideal PLL-CCI given current calculated from the IP-CCI given power 1240W is equal to 8A. As depicted in Fig. 3 and Fig. 4, the red lines and black lines represent the frequency response characteristics of the SAs and CAs of the studied CCIs, respectively; while the blue and pink dots stand for the corresponding measurement results. From Fig. 3, conclusions can be drawn as follows: 1) The admittance measurement results show great consistency with the derived admittance models, thus validating the IP-CCI sequence-admittance modeling; 2) As shown with the light blue shadow rectangles, the magnitude characteristics of the SAs and that of the CAs are close to each other under 1500Hz near to the bandwidth of the current control loop, which means that the SA and CA couple with each other in a wide frequency range; 3) From the phase frequency characteristics, it can be observed that the phases of $Y^p_{IP}(s)$ and $Y^n_{IP}(s)$ are within $[-90^\circ, 90^\circ]$, which illustrates $Y^p_{IP}(s)$ and $Y^n_{IP}(s)$ present positive damping characteristics in the studied frequency range. Although the phases of $Y^p_{IP}(s)$ and $Y^n_{IP}(s)$ exhibit a sudden change of 180° at 50Hz due to the resonant term in the PR controller, it would not result in resonances.

By comparison, it can be seen from the light blue shadow rectangles in Fig. 4 that the SAs and CAs of the PLL-CCI have close couplings only in low-frequency range, which is much narrower than that of the IP-CCI. That is because the PLL has a filter in the control loop, which reduces the magnitude of $J^p_{PLL}(s)$ and $J^n_{PLL}(s)$ greatly above the bandwidth of the PLL. However, ND regions (NDRs) shown as grey shadows are introduced to the $Y^p_{PLL}(s)$ and $Y^n_{PLL}(s)$ around 50Hz, it is due to the well-known PLL. If resonant points locate in the NDRs, instability would be triggered. Therefore, sequence-admittances of the IP-CCI exhibit some differences in comparison to the PLL-CCI, interactive instability towards the IP-CCI needs to be revealed considering the strong sequence-couplings.

### III. COUPLING-RELATED DAMPING CHARACTERISTICS ANALYSIS OF THE IP-CCI

#### A. DERIVATION AND ANALYSIS OF EQUIVALENT SEQUENCE-ADMITTANCE MODELS

It has been widely recognized that sequence-admittance-based stability of grid-connected CCIs is analyzed by the minor loop gain, which is defined as the ratio of the CCI and grid admittance as written in (24). In (24), $Y_p(s)$ and $Y_n(s)$ represent the positive- and negative-sequence admittances of the CCI, $Y_{gp}(s)$ and $Y_{gn}(s)$ denote the positive- and negative-sequence admittances of the grid, $H_p(s)$ and $H_n(s)$ represent the positive- and negative-sequence admittance ratio, respectively. If we assume that the inverter is stable when connected to a grid with zero impedance, and the grid is stable when an ideal current source with infinite impedance connected to it, then only if $H_p(s)$ and $H_n(s)$ don’t circle $(-1, j0)$, the system is stable [13]. However, the admittance-ratio based stability analysis models ignore sequence-couplings. As indicated in Fig. 3 and Fig. 4, sequence-couplings of the IP-CCI cannot be neglected within 1500Hz, and that of the PLL-CCI cannot be neglected near 50Hz. Take the sequence-couplings into consideration,
the SISO stability analysis models are modified by the MIMO admittance-matrix-based analysis model $L_{PN}(s)$ as shown in (25) [16], where $J_p(s)$ and $J_n(s)$ are included, $Z_{gp}(s)$ and $Z_{gn}(s)$ are the positive- and negative-sequence impedances of the grid. By means of the MIMO model, accurate stability judgements can be derived according to the generalized Nyquist criterion, but it fails in getting clear insight of the instability mechanism from $L_{PN}(s)$. Please note that admittances in this section denote the generalized admittances, which omit relevant superscripts.

\[
H_p(s) = \frac{Y_p(s)}{Y_{gp}(s)}, \quad H_n(s) = \frac{Y_n(s)}{Y_{gn}(s)} \tag{24}
\]

\[
L_{PN}(s) = \begin{bmatrix}
Z_{gp}(s) & 0 \\
0 & Z_{gn}(s - 2j\omega_1)
\end{bmatrix}
\begin{bmatrix}
Y_p(s) \\
J_p(s - 2j\omega_1)
\end{bmatrix}
\tag{25}
\]

Furthermore, the SISO equivalent sequence-admittance (ESA) models are derived here. Take the positive-sequence voltage perturbation and current response process as an example, the interaction process of the CCI and the grid can be shown in Fig. 5. As the red arrows depicted, the sequence-couplings of the inverter itself and the circuit-coupling between the inverter and the grid together add a paralleled branch to the output current response at the disturbed frequency. Then the generated positive-sequence current influenced by sequence-couplings can be inferred as $I_{pp}$:

\[
I_{pp}(s) = -\frac{V_p(s)}{1 + Z_{gp}(s)} \left[ Y_p(s) - \frac{J_p(s)J_n(s \mp j2\omega_1)Z_{gn}(s \mp j2\omega_1)}{1 + Y_n(s \mp j2\omega_1)Z_{gn}(s \mp j2\omega_1)} \right] \tag{26}
\]

\[
\begin{aligned}
&V_p(s) \quad \text{(inverter)} \\
&\rightarrow Z_{gp}(s) \\
&\rightarrow Y_p(s) \quad \text{positive-sequence admittance} \\
&\rightarrow Y_p(s) \quad \text{current response} \\
&\rightarrow I_{pp}(s) \quad \text{sequence-coupling} \\
&|I_{pp}| \\
&\rightarrow I_{pp}(s) \quad \text{current response} \\
&\rightarrow \text{current of the grid}
\end{aligned}
\]

\[
\begin{aligned}
&\text{Sequence-coupling} \\
&\text{Circuit-coupling}
\end{aligned}
\]

\[
\text{FIGURE 5. Positive-sequence voltage perturbation and current response considering sequence-couplings.}
\]

From (26), we can obtain the equivalent positive-sequence admittance model as:

\[
Y_{ep}(s) = Y_p(s) - \frac{J_p(s)J_n(s \mp j2\omega_1)Z_{gn}(s \mp j2\omega_1)}{1 + Y_n(s \mp j2\omega_1)Z_{gn}(s \mp j2\omega_1)} \tag{27}
\]

Similarly, the equivalent negative-sequence admittance model can be described as:

\[
Y_{en}(s) = Y_n(s) - \frac{J_n(s)J_p(s \pm j2\omega_1)Z_{gp}(s \pm j2\omega_1)}{1 + Y_p(s \pm j2\omega_1)Z_{gp}(s \pm j2\omega_1)} \tag{28}
\]

By analysis of the modified admittance-ratio $Y_{ep}(s)/Y_{gp}(s)$ and $Y_{en}(s)/Y_{gn}(s)$ according to the Nyquist criterion, coupling-related instability mechanism and status can be recognized.

Additionally, it can be noticed from (27) and (28) that paralleled admittance terms are introduced because of the sequence-couplings and circuit-coupling, which are defined as coupling-induced admittances (CIAs) written as the following $Y_{ep}(s)$ and $Y_{en}(s)$. If $J_p(s)$ and $J_n(s)$ are much smaller than $Y_p(s)$ and $Y_n(s)$, $Y_{ep}(s) \approx Y_p(s)$ and $Y_{en}(s) \approx Y_n(s)$. If $Z_{gn}(s) = 0$, $Y_{ep}(s) = Y_p(s)$ and $Y_{en}(s) = Y_n(s)$.

\[
\begin{aligned}
Y_{ep}(s) &= \frac{J_p(s)J_n(s \mp j2\omega_1)Z_{gp}(s \mp j2\omega_1)}{1 + Y_n(s \mp j2\omega_1)Z_{gp}(s \mp j2\omega_1)} \tag{29} \\
Y_{en}(s) &= \frac{J_n(s)J_p(s \pm j2\omega_1)Z_{gp}(s \pm j2\omega_1)}{1 + Y_p(s \pm j2\omega_1)Z_{gp}(s \pm j2\omega_1)} \tag{30}
\end{aligned}
\]

Moreover, the IP-CCI is chosen to validate the developed models have a good match with the measurement results of ESA models are depicted in Fig. 6, where $Y_{IP}^{ep}(s)$ and its measurement result are depicted as red line and blue dots; $Y_{IP}^{en}(s)$ and its measurement result are depicted as black line and pink dots. It can be concluded that the developed models have a good match with the measurement results, which confirms that the $Y_{ep}(s)$ and $Y_{en}(s)$ can describe the terminal behavior of the CCIs well.

\[
\text{FIGURE 6. Equivalent sequence admittances of the IP-CCI and their simulation measurement results.}
\]

As for the ESA, its frequency characteristics can be recognized by analysis of the dominant admittance term. Take the analysis of $Y_{ep}(s)$ for example, three cases can be expected as shown in Fig. 7:

\[
\text{FIGURE 7. The relationship of } Y_{ep}(s), Y_p(s) \text{ and } Y_{gp}(s) \text{ in complex plane:} \\
(a) |Y_p(s)| \gg |Y_{ep}(s)|, (b) |Y_{ep}(s)| \gg |Y_p(s)|, (c) |Y_{ep}(s)| \text{ is close to } |Y_p(s)|.
\]

1) The SA is the dominant admittance. As shown in Fig. 7(a), the amplitude of $Y_p(s)$ is far greater than that of $Y_{ep}(s)$, namely, $|Y_p(s)| \gg |Y_{ep}(s)|$, so $Y_{ep}(s) \approx Y_p(s)$. Therefore, the frequency characteristics of $Y_{ep}(s)$ are
dominated by \( Y_p(s) \). It means that couplings have limited contribution.

2) The CIA is the dominant admittance. Contrary to the first case, as shown in Fig. 7(b), \( Y_{ep}(s) \gg Y_p(s) \), so \( Y_{ep}(s) \approx Y_p(s) \). Therefore, the frequency characteristics of \( Y_{ep}(s) \) are dominated by \( Y_p(s) \) and the terminal behavior of the CCI has close relationships with couplings.

3) The SA and CIA are comparable. As depicted in Fig. 7(c), the amplitude of \( Y_p(s) \) is close to that of \( Y_{ep}(s) \). In this case, the frequency characteristics of \( Y_{ep}(s) \) can be quite different from \( Y_p(s) \) and \( Y_{cp}(s) \). Frequency characteristics of the ESA should be determined according to further analysis.

B. COUPLING-RELATED DAMPING CHARACTERISTICS RECOGNITION OF CCIS BASED ON THE ESA

Former studies on damping features only paid attention on the control dynamics of the grid-connected CCI itself, by improving the passivity of each CCI to avoid interactive instability as much as possible [24]. While, as seen from Fig. 5, if sequence-couplings are taken into consideration, the grid impedance would further interact with control dynamics of the CCI and influence damping behaviors of the CCI at the PCC, which cannot be found just by analysis of the CCI itself. Additionally, For the damping behavior of the CCIs, it has been inferred that it is the ND that could result in instability. Considering the couplings, corresponding ND is named as the coupling-related ND (CND) here.

It can be inferred that the CIA has relationships not only with parameters of the CCI, but with the grid impedance. Therefore, to have a first recognition of the CND, the strong grid with \( L_g = 2\text{mH} \) and weak grid with \( L_g = 12\text{mH} \) are chosen to simulate the weak coupling and strong coupling case, respectively. Other parameters are the same as shown in Table 1. Please note that the system parameters are designed to have attenuated high-frequency ND related to the time delay and the LCL-filter.

The damping characteristics can be recognized by ND regions (NDRs) depicted in the Bode plots with phase exceeding \([-90°,90°]\). Here, the NDR located at above 800Hz is defined as high-frequency NDR (HNDR), the NDR ranging from 200Hz to 800Hz is called middle-frequency NDR (MNDR), and the NDR below 200Hz is clarified as low-frequency NDR (LNDR). In Fig. 8 and Fig. 9, the coupling-related NDRs (CNDRs) derived from \( Y_{ep}(s) \) are shown as yellow shadow regions. The \( Y_p(s) \), \( Y_{cp}(s) \) and \( Y_{ep}(s) \) are plotted by red line, orange line and black line, respectively. As \( Y_{ep}(s) \) and \( Y_{cp}(s) \) are grid-impedance-dependent, when \( L_g = 2\text{mH} \), they are depicted as solid lines, and when \( L_g = 12\text{mH} \), they are depicted as dotted lines.

1) COUPLING-RELATED DAMPING CHARACTERISTICS RECOGNITION OF THE PLL-CCI

For the PLL-CCI, Fig. 8 shows the corresponding relationship of \( Y^{PLL}_{PLL}(s) \), \( Y^{PLL}_{CP}(s) \) and \( Y^{PLL}_{EP}(s) \) by means of Bode plots. It can be seen that no matter \( L_g = 2\text{mH} \) or \( L_g = 12\text{mH} \), it satisfies \( |Y_{PLL}^{PLL}(s)| \gg |Y_{PLL}^{PLL}(s)| \) in the depicted frequency range, which is consistent with the case shown in Fig. 7(a). That means the SA is the dominant admittance and the frequency characteristics of \( Y_{ep}^{PLL}(s) \) are mostly determined by \( Y_p^{PLL}(s) \). For red-line-depicted \( Y_p^{PLL}(s) \), it only has an LNDR as seen from the enlarged Bode plots between 120Hz and 180Hz, which stems from the PLL. That’s to say, it is the PLL that results in the low-frequency ND to the PLL-CCI considering the couplings or not. Although \( Y_{PLL}^{PLL}(s) \) of the PLL-CCI also has NDRs, it could not trigger CND above 200Hz because of its small magnitude compared with \( Y_p^{PLL}(s) \). Even so, it should be noticed that \( |Y_{cp}^{PLL}(s)| \) becomes larger with the increase of the grid impedance, which means the influence of couplings increases as well. Compare the grey and the yellow shadow regions in the enlarged Bode plots, the CNDR is clearly widened when \( L_g = 12\text{mH} \), which means couplings could enlarge the NDR of the PLL-CCI. Therefore, as [16] clarified that incorrect stability conclusion may be draw if sequence-couplings are neglected.

2) COUPLING-RELATED DAMPING CHARACTERISTICS RECOGNITION OF THE IP-CCI

For the IP-CCI, the corresponding relationship of \( Y_{IP}^{IP}(s) \), \( Y_{IP}^{CP}(s) \) and \( Y_{IP}^{EP}(s) \) is shown in Fig. 9. Firstly, it can be concluded from the orange lines, as the same as that of the PLL-CCI, the magnitude of \( Y_{IP}^{IP}(s) \) increases with the increase of the grid impedance. Differently, the magnitude frequency curves of \( Y_{IP}^{IP}(s) \) and \( Y_{IP}^{CP}(s) \) have several intersections, which means the dominant admittance is different in different frequency range, especially in weak grid. In Fig. 9, when \( L_g = 2\text{mH} \), as seen from the solid lines, Bode plots of \( Y_{IP}^{IP}(s) \) are almost as the same as the \( Y_{IP}^{IP}(s) \) in the low- and middle-frequency range. Although \( |Y_{IP}^{IP}(s)| \) and \( |Y_{IP}^{IP}(s)| \) intersect at point A, from the corresponding phase frequency curves, it can be concluded that NDR of \( Y_{IP}^{IP}(s) \) can be attenuated by \( Y_{IP}^{IP}(s) \). Therefore, \( Y_{IP}^{IP}(s) \) shows positive damping characteristics like \( Y_{IP}^{IP}(s) \). Whereas, when \( L_g \) is increased to
be 12mH, six intersections of the red line and dotted orange line can be observed in Fig. 9, denoted as green dots. When $|Y_{ep}(s)| > |Y_{ip}(s)|$, frequency characteristics of the $Y_{ip}(s)$ are more related with the $Y_{ep}(s)$, such as the light blue areas, so CNDRs located in middle- and high-frequency range are introduced to the $Y_{ep}(s)$ via couplings as shown in the yellow shadow regions.

In conclusion, for the IP-CCI, couplings totally result in the CNDRs. As the coupling terms written in (29) and (30) are grid-impedance-dependent, the CNDRs are greatly influenced by the varied grid impedance. In specific weak grid, the circuit-coupling is changeless, so the CND would be determined by the sequence-coupling degree.

3) OVERALL COUPLING-RELATED DAMPING CHARACTERISTICS RECOGNITION OF THE IP-CCI

Compare the above CND analysis of the IP-CCI with that of the PLL-CCI, clearer damping characteristics can be recognized. It shows that ND of the PLL-CCI stems from the SAs and the couplings just enlarge the frequency range of the NDR. While, the ND of the IP-CCI comes from the couplings completely, new NDRs may be generated from interactions of sequence-couplings and circuit-coupling. However, for both of them, with the increase of the grid impedance, the influence of couplings on ND characteristics is increased simultaneously.

Moreover, three approaches can be inferred to mitigate the CND as follows: 1) Reduce the magnitude of $Y_{ep}(s)$ to satisfy $|Y_{ep}(s)| << |Y_{ip}(s)|$ as far as possible; 2) Decrease the NDR of $Y_{ep}(s)$; 3) Eliminate the sequence-couplings completely. For the PLL-CCI, all the three methods are feasible, but it can be concluded that even if the sequence-couplings are fully eliminated, which means $j_{p}^{PLL}(s)$ and $j_{n}^{PLL}(s)$ are zero, NDR still exists in the SAs and influences the system stability under weak grid, which is consistent with conclusions in [25]. When it comes to the IP-CCI, it can be drawn from the admittance modeling process that sequence-couplings are inherent in the instantaneous power theory and impossible to be eliminated. Therefore, only the first two methods are applicable. As the referenced power, the current controller and the grid impedance can influence the $Y_{ip}(s)$ directly, corresponding instability analysis of the IP-CCI under different system parameters will be carried out in the following sections to help us explore the instability deeply and design the grid-connected CCI reasonably.

IV. COUPLING-RELATED INSTABILITY ANALYSIS OF THE IP-CCI UNDER DIFFERENT SYSTEM PARAMETERS

In this section, influences of system parameters on the coupling-related instabilities of the IP-CCI are analyzed by means of the Bode plots, from which it can be clearly seen the resonant points indicating by intersections of $Y_{ep}(s)$ and $Y_{ip}(s)$, and their damping features. Then, regarding the inductive grid, instable conclusions can be drawn according to the criteria: 1) The magnitude-frequency plot of $Y_{ep}(s)$ and that of $Y_{ip}(s)$ have intersections; 2) The intersections fall into the NDR with phase exceeding 90°.

A. COUPLING-RELATED INSTABILITY ANALYSIS OF THE IP-CCI UNDER DIFFERENT GRID INDUCTANCE

Fig. 10 shows the relationships of $Y_{ip}(s)$ and $Y_{ip}(s)$ under different grid inductance, other parameters keep consistent with those in Table 1. Different from interactive instability analysis neglecting the sequence-coupling, $Y_{ip}(s)$ would vary with the varied $L_{g}$ as observed from Fig. 10, which complicates the resonant points and corresponding damping analysis.

In general, when $L_{g} = 6\text{mH}$, it has no NDR existing; when $L_{g} = 8\text{mH}$, there is only HNDR appearing; when $L_{g} = 10\text{mH}$ and $L_{g} = 12\text{mH}$, the MNDR is brought in besides the high-frequency one. However, it doesn’t mean that all the NDRs can result in instability. Only when the resonant points exist, unstable states could be triggered. In Fig. 10, possible interactive resonant points are depicted with dots A, B, a, b, c and d. The color of each dot keeps consistent with the intersecting admittance curves, the capital letters represent the high-frequency resonant points and the lower-case letters denote the middle-frequency resonant points. Therefore, it can be concluded that the IP-CCI is stable with $L_{g} = 6\text{mH}$ (no NDR), while the IP-CCI resonates at high frequencies with $L_{g} = 8\text{mH}$ (HNDR+A), and the IP-CCI oscillates at
middle frequencies with $L_g = 10\text{mH}$ (MNDR+c) and $L_g = 12\text{mH}$ (MNDR+d). Therefore, the increased grid inductance would deteriorate the coupling-related instability. Additionally, the resonant point shifts towards lower frequencies when the grid inductance varies from $10\text{mH}$ to $12\text{mH}$, shown as c and d. It can be further clarified that the resonant frequencies tend to be smaller with the grid inductance increasing.

**B. COUPLING-RELATED INSTABILITY ANALYSIS OF THE IP-CCI DESIGNED WITH DIFFERENT PARAMETERS**

Here, the grid impedance is chosen to be $12\text{mH}$. Compared with parameters in Table 1, the IP-CCI is designed with reduced given power reference, reduced resonant coefficient and reduced proportional coefficient, respectively. Corresponding coupling-related instability judgement and mechanism recognition are carried out as follows.

As shown in Fig. 11, compare the blue lines with the pink lines, when the power reference is reduced from $1240\text{W}$ to $930\text{W}$, no CNDR is triggered. Therefore, the resonance at point d in Fig. 10 would be eliminated with smaller grid-injected active power. Compared with the pink lines, the black lines are designed with resonant coefficient $K_p$ decreased from $1500$ to $500$. It can be seen that the MNDR in Fig. 10 disappears, but the HNDR in Fig. 10 still exists. Moreover, new high-frequency resonant point depicted with the black dot D is introduced, which means the high-frequency instability is triggered. Therefore, we can conclude that decreasing $K_p$ is good for attenuating the middle-frequency instability, but may deteriorate the high frequency stability. If the proportional coefficient $K_p$ is decreased from 10 to 8, it can be clearly observed from comparison of the red lines and pink lines that the HNDR in Fig. 10 disappears and the MNDR in Fig. 10 is narrowed. Although resonance still exists as depicted with the red point d, we can deduce that decreasing $K_p$ mitigates both the middle-frequency and high-frequency instabilities.

To recognize the above CNDR mitigation and deterioration deeply, Fig. 12 depict frequency characteristics of the $Y_{cp}^{IP}(s)$ and $Y_{cp}^{IP}(s)$ under different circumstances when $L_g = 12\text{mH}$. By comparisons, it can be concluded that: 1) Reducing the active power can decrease the magnitude of $Y_{cp}^{IP}(s)$ effectively in the studied frequency range (compare the solid blue line with the solid pink line), which means wide-frequency couplings are effectively weakened by the smaller grid-connected active power. 2) Reducing the resonant coefficient increases the magnitude of $Y_{cp}^{IP}(s)$ in the low-frequency range and decreases the magnitude of $Y_{cp}^{IP}(s)$ from about $230\text{Hz}$ to $1300\text{Hz}$ (compare the dot black line with the dot pink line), and also decreases the magnitude of $Y_{cp}^{IP}(s)$ (compare the solid black line with the solid pink line) in the middle-frequency range. That denotes the resonant coefficient has a large effect on attenuation of middle-frequency couplings. 3) When the proportional coefficient is decreased, couplings between $Y_{cp}^{IP}(s)$ and $Y_{cp}^{IP}(s)$ are reduced above $300\text{Hz}$ (compare the red lines with the pink lines). Therefore, reducing the proportional coefficient can attenuate middle- and high-frequency couplings. Although the phase also changes with different parameters, the magnitude tells more about the couplings.

![FIGURE 11. Relationships of the $Y_{cp}^{IP}(s)$ and $Y_{g}(s)$ of the IP-CCI designed with different parameters when $L_g = 12\text{mH}$.](image)

![FIGURE 12. The relationship of $Y_{cp}^{IP}(s)$ and $Y_{cp}^{IP}(s)$ of the IP-CCI designed with different parameters when $L_g = 12\text{mH}$.](image)
Usually, the grid injected active power represent the steady-state characteristics, it cannot be decreased randomly. Therefore, the $J_p^IP(s)$ can only be redesigned by current controller regulation. As seen from Fig. 12, although current controller parameters regulation also changes frequency characteristics of SAs to some extent, the main changes appear at low-frequency range near 50Hz. In the middle-frequency range, the CAs vary apparently with varied controller parameters, which determines more to the coupling-related instability. For the CAs in (16) and (18), it is interesting that they contain the closed-loop transfer functions of the current control, which is written as (31). Therefore, $J_p^IP(s) = G_c(s)P/(V^2G_e(f_1))$. Then, parameters regulation of the IP-CCI to ensure the stability of the interconnected CCI and grid are clearer and easier. Moreover, dynamical performance can also be considered simultaneously. Controller parameters regulation of the IP-CCI considering both the stability and dynamical response is another issue to be clarified, limited by the article space, it is not conduced in this paper.

$$G_c(s) = \frac{H_{tw}(s)G_e(s \pm j2\omega_0)G_d(s)}{P(s) + H_{tw}(s)G_e(s)G_d(s)} \quad (31)$$

### C. COUPLING-RELATED INSTABILITY ANALYSIS OF THE IP-CCI WITH ADDED FILTERS

Previous work towards the IP-CCI has referred that the filter is needed to eliminate the harmonic instabilities under weak grids [12], but it is short of corresponding analysis. Here, we choose the low pass filter (LPF) and band pass filter (BPF) based instability attenuation methods to figure out their mitigation mechanism from the sequence-admittances.

The filter is usually added to the sampled voltages in Fig. 1. If the filter denoted as $G_b(s)$ is introduced into the IP-CCI, its sequence-admittances are modified as (32), where only the CAs are modified by the added filters.

$$\begin{align*}
Y_{pb}(s) &= Y_p^{IP} + J_p^IP(s)Gb(s \pm j2\omega_1) \quad f = \pm f_p \\
J_{pb}(s) &= \frac{J_p^IP(s)Gb(s \pm j2\omega_1)}{G_b^P(\pm j\omega_1)} \quad f = \pm (f_p - 2f_1) \\
Y_{nb}(s) &= Y_n^{IP} \quad f = \pm f_n \\
J_{nb}(s) &= \frac{J_n^IP(s)Gb(s \pm j2\omega_1)}{G_b^P(\pm j\omega_1)} \quad f = \pm (f_n + 2f_1)
\end{align*} \quad (32)$$

Corresponding descriptions of the LPF and the BPF are written as:

$$G_b^L(s) = \frac{2\pi f_{LPF}}{s + 2\pi f_{LPF}}, \quad G_b^B(s) = \frac{2\omega_c s}{s^2 + 2\omega_c s + \omega_c^2} \quad (33)$$

where $f_{LPF}$ is the cut-off frequency of the LPF, $\omega_c = \xi \omega_0$ is the resonance bandwidth, $\omega_0$ is the resonance frequency and $\xi$ is the damping ratio.

Fig. 14 (a) depict the positive-sequence SA and CA of the IP-CCI with LPFs equipped with different $f_{LPF}$, and Fig. 14 (b) depict the positive-sequence SA and CA of the IP-CCI with BPFs designed with different $\omega_c$. By comparisons with Fig. 3, we can see that both filters achieve the decoupling of SA and CA in middle and high frequency range greatly, and the decoupling degree is enhanced with the decreased $f_{LPF}$ and $\omega_c$. As seen from the above analysis, coupling-related instabilities are more serious with the larger grid impedance. Therefore, the weaker grid requires the smaller $f_{LPF}$ and $\omega_c$. That is similar with the PLL, whose bandwidth $f_{PLL}$ should be smaller under weak grids to ensure the stability. Additionally, the relationship of SAs and CAs of the IP-CCI is like with that of the PLL-CCI as shown in Fig. 4, because the added filter imitates the filter function of the proportional-integral controller in PLL.

![FIGURE 13. Bode diagrams of $J_p^IP(s)$ of the IP-CCI designed with different parameters when $L_g = 12mH$.](image)

![FIGURE 14. Sequence admittances of the IP-CCI with filters: (a) IP-CCI with LPFs, (b) IP-CCI with BPFs.](image)

To further exhibit the performance of the filter, an LPF with $f_{LPF} = 200Hz$ is added to the IP-CCI, and the IP-CCI is connected to a weak grid with $L_g = 12mH$. Other parameters of the IP-CCI keep consistent with those in Table 1. Fig. 15 shows the corresponding sequence-admittances and the grid admittance. It can be seen from the pink lines that both the HNDR and MNDR in Fig. 10 are eliminated by the added filters. As seen from the above analysis, coupling-related instabilities are more serious with the larger grid impedance. Therefore, the weaker grid requires the smaller $f_{LPF}$ and $\omega_c$. That is similar with the PLL, whose bandwidth $f_{PLL}$ should be smaller under weak grids to ensure the stability. Additionally, the relationship of SAs and CAs of the IP-CCI is like with that of the PLL-CCI as shown in Fig. 4, because the added filter imitates the filter function of the proportional-integral controller in PLL.

![FIGURE 14. Sequence admittances of the IP-CCI with filters: (a) IP-CCI with LPFs, (b) IP-CCI with BPFs.](image)

To further exhibit the performance of the filter, an LPF with $f_{LPF} = 200Hz$ is added to the IP-CCI, and the IP-CCI is connected to a weak grid with $L_g = 12mH$. Other parameters of the IP-CCI keep consistent with those in Table 1. Fig. 15 shows the corresponding sequence-admittances and the grid admittance. It can be seen from the pink lines that both the HNDR and MNDR in Fig. 10 are eliminated by the added filters. As seen from the above analysis, coupling-related instabilities are more serious with the larger grid impedance. Therefore, the weaker grid requires the smaller $f_{LPF}$ and $\omega_c$. That is similar with the PLL, whose bandwidth $f_{PLL}$ should be smaller under weak grids to ensure the stability. Additionally, the relationship of SAs and CAs of the IP-CCI is like with that of the PLL-CCI as shown in Fig. 4, because the added filter imitates the filter function of the proportional-integral controller in PLL.
A. NYQUIST STABILITY ANALYSIS

According to stability analysis model $\frac{Y_{ep}(s)}{Y_{gp}(s)}$, intuitive Nyquist analysis are shown in Fig. 16, Fig. 17 and Fig. 18.

Fig. 16 shows the corresponding Nyquist analysis of the studied grid-connected IP-CCI under different grid inductances. From Fig. 16, it can be seen that the Nyquist curves don’t encircle the critical point $(-1, j0)$ when $L_g = 6mH$ and encircle $(-1, j0)$ when $L_g = 8mH$, $L_g = 10mH$ and $L_g = 12mH$, which means that the system is stable only when $L_g = 6mH$. Apart from the derived stability conclusions, it should be noted that the Nyquist curves in each case includes a big circle indicated as A and a small circle indicated as B, which are the characteristics of coupling-related instability specialized in this paper. For the big circle, its intersections with the unit circle indicate the high-frequency stability condition; and the intersections of the small circle and the unit circle illustrate the middle-frequency stability mode. If the two circles intersect with the unit circle and encircle $(-1, j0)$, oscillations would be triggered in the corresponding frequency range. Therefore, when $L_g = 10mH$ and $L_g = 12mH$, only middle-frequency resonance occurs in the system. While, high-frequency resonance is generated in the grid-connected currents when $L_g = 8mH$. That verifies the ND analysis of resonant points c, d and B in Fig. 11.

The instability analysis in Fig. 11 is also validated by the characteristic loci of $\{\frac{Y_{ep}(s)}{Y_{gp}(s)}\}$ in Fig. 17. By varying the system parameters, triggered oscillations have different features when $L_g = 12mH$. Fig. 17(a) shows a stable system with the reduced active power; Fig. 17(b) indicates the vanished middle-frequency resonance and triggered high-frequency resonance with the decreased resonant coefficient and Fig. 17(c) shows the still existing middle-frequency resonance. Unstable cases in Fig. 17(b) and (c) validate resonances at the black dot D and the red dot d in Fig. 11, respectively.

Fig. 18 depicts the characteristic loci of the IP-CCI with an LPF with $f_{LPF} = 200Hz$, it can be drawn that even though the IP-CCI is unstable when $L_g = 12mH$, the IP-CCI turns to be stable with the LPF introduced.
B. TIME-DOMAIN SIMULATION RESULTS
With the designed parameters in Table 1, Fig. 19 shows the time-domain simulation waveforms of the IP-CCI under different grid inductances. From Fig. 19, it can be seen when \( L_g = 6\, \text{mH} \), the system is stable and when \( L_g = 8\, \text{mH} \), the system oscillates approximately at near 1090Hz and 1190Hz. The same way, the system oscillates at about 170Hz and 270Hz when \( L_g = 10\, \text{mH} \); when \( L_g = 12\, \text{mH} \), oscillation occurs at about 160Hz and 260Hz. Moreover, we can deduce that whether it is in high-frequency range or in middle-frequency range, the resonant frequencies appear in pairs, which confirms the instability issues suffering from the sequence-couplings. Additionally, the resonant frequencies become smaller with the grid inductance increasing.

Simulations in Fig. 20 depict corresponding waveforms of the IP-CCI equipped with reduced \( P_r \), \( K_r \) and \( K_p \). The simulation results are consistent with the ND analysis in Fig. 11 and Nyquist analysis in Fig. 17. Coupling-induced resonances in high-frequency and middle-frequency range are verified further. Time-domain sinusoidal waveforms in Fig. 21 verify the effectiveness of the LPF-based instability mitigation method.

C. EXPERIMENTAL RESULTS
To experimentally verify the coupling-related instability phenomena of the IP-CCI, a three-phase LCL-filtered 5-kW inverter system is built in the lab as shown in Fig. 22. The control schemes are implemented in TI DSP TMS320F28335. A 2:1 transformer is used to connect the LCL-filtered VSI to the grid. The variable inductance ranging from 2mH to 10mH is used to represent the grid impedance. Parameters of the platform are consistent with those in Table 1.

Fig. 23 shows the grid-connected voltages, currents and the THD of the currents at different grid inductance. It can
be seen when $L_g = 4\, \text{mH}$, the grid-connected IP-CCI can run stably; when $L_g = 6\, \text{mH}$, the system oscillates mainly at 400Hz and 500Hz; when $L_g = 8\, \text{mH}$, the resonant frequencies shift to 300Hz and 400Hz. The frequency spectrum indicates that the resonant frequencies are in pairs and move to lower frequency bands with the increasing grid inductance, which proves the coupling-induced instability of the IP-CCI.

Fig. 24 shows grid-connected currents of the IP-CCI equipped with reduced $P_r$, $K_r$ and $K_p$ when $L_g = 8\, \text{mH}$, it verifies that coupling-related harmonic instabilities (300Hz and 400Hz) of the IP-CCI can be attenuated with smaller injected active power, smaller resonant and smaller proportional coefficient. When the LPF-based decoupling scheme is implemented, the grid-connected IP-CCI with $L_g = 8\, \text{mH}$ is observed to be stable as seen in Fig. 25.

Therefore, the coupling-related instability phenomena are validated by the experimental results. Because of the imperfect experiment equipment, some tolerable differences existing between the theoretical analysis and the experiments.

VI. CONCLUSION

In this paper, instability mechanism and mitigation of the IP-CCI are analyzed from the coupled-sequence-admittance models by comparison with the PLL-CCI. Specially,
the instability of the IP-CCI is firstly studied from its terminal admittance characteristics, and the corresponding controller regulation and filter-based instability mitigation mechanism is clearly clarified. Conclusions can be drawn as follows:

1) The coupling-related instability is related to the design of the IP-CCI and also it is grid-impedance-dependent, so it is the consequence of interactions between the sequence-couplings and circuit-coupling;

2) Differently from the PLL-CCI, whose sequence-couplings just enlarge the frequency range of the negative damping. With no restrictions of the PLL, the IP-CCI has no negative damping regions in low-frequency range, but middle-frequency and high-frequency negative damping can be generated due to the strong couplings;

3) For the IP-CCI, the coupling-related instability can be removed by mitigation methods contributing to reduce the magnitude of the coupled-admittances at resonant frequencies as much as possible. For example, decreasing the resonant coefficient works for eliminating middle-frequency instabilities, decreasing the proportional coefficient helps to mitigate both middle- and high-frequency instabilities. Additionally, the extra filters are effective to ensure the stability of the IP-CCI in a wide frequency range.

REFERENCES

[1] J. Rocabet, A. Luna, F. Blaabjerg, and P. Rodriguez, “Control of power converters in AC microgrids,” IEEE Trans. Power Electron., vol. 27, no. 11, pp. 4734–4749, Nov. 2012.

[2] M. Ashabani and J. Jung, “Synchronous voltage controllers: Voltage-based emulation of synchronous machines for the integration of renewable energy sources,” IEEE Access, vol. 8, pp. 49497–49508, 2020.

[3] Y. Yu, H. Li, Z. Li, and Z. Zhao, “Modeling and analysis of resonance in LCL-type grid-connected inverters under different control schemes,” Energies, vol. 10, no. 1, p. 104, Jan. 2017.

[4] X. Wang and F. Blaabjerg, “Harmonic stability in power electronic-based power systems: Concept, modeling, and analysis,” IEEE Trans. Smart Grid, vol. 10, no. 3, pp. 2858–2870, May 2019.

[5] M. Liserre, R. Teodorescu, and F. Blaabjerg, “Stability of photovoltaic and wind turbine grid-connected inverters for a large set of grid impedance values,” IEEE Trans. Power Electron., vol. 21, no. 1, pp. 263–272, Jan. 2006.

[6] M. Cespedes, “Impedance modeling, analysis, and adaptation of grid-connected inverters with PLL,” Ph.D. dissertation, Dept. Elect. Eng., Rensselaer Polytech. Inst., Troy, NY, USA, 2014.

[7] Z. Xie, Y. Chen, W. Wu, Y. Xu, H. Wang, J. Guo, and A. Luo, “Modeling and control parameters design for grid-connected inverter system considering the effect of PLL and grid impedance,” IEEE Access, vol. 8, pp. 40474–40484, 2020.

[8] D. Dong, B. Wen, D. Boroyevich, P. Mattavelli, and Y. Xue, “Analysis of phase-locked loop low-frequency stability in three-phase grid-connected power converters considering impedance interactions,” IEEE Trans. Ind. Electron., vol. 62, no. 1, pp. 310–321, Jan. 2015.

[9] Z. Zhang, W. Wu, Z. Shuai, X. Wang, A. Luo, H. S.-H. Chung, and F. Blaabjerg, “Principle and robust impedance-based design of grid-tied inverter with LCL-filter under wide variation of grid-reactance,” IEEE Trans. Power Electron., vol. 34, no. 5, pp. 4362–4374, May 2019.

[10] S. Guler, V. M. Iyer, and S. Bhattacharya, “Stationary reference frame based current control structure with improved disturbance rejection for grid connected converters,” in Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC), San Antonio, TX, USA, Mar. 2018, pp. 1031–1035.

[11] J. G. Hwang, P. W. Lehn, and M. Winkelnkemper, “A generalized class of stationary frame-current controllers for grid-connected AC–DC converters,” IEEE Trans. Power Del., vol. 25, no. 4, pp. 2742–2751, Oct. 2010.

[12] Y. Gui, X. Wang, and F. Blaabjerg, “Vector current control derived from direct power control for grid-connected inverters,” IEEE Trans. Power Electron., vol. 34, no. 9, pp. 9224–9235, Sep. 2019.

[13] J. Sun, “Impedance-based stability criterion for grid-connected inverters,” IEEE Trans. Power Electron., vol. 26, no. 11, pp. 3075–3078, Nov. 2011.

[14] A. Rygg, M. Molinas, C. Zhang, and X. Cai, “A modified sequence-domain impedance definition and its equivalence to the dq-domain impedance definition for the stability analysis of AC power electronic systems,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 4, no. 4, pp. 1383–1396, Dec. 2016.

[15] S. Shah and L. Parsa, “Impedance modeling of three-phase voltage source converters in DQ, sequence, and phasor domains,” IEEE Trans. Energy Convers., vol. 32, no. 3, pp. 1139–1150, Sep. 2017.

[16] M. K. Bakshihzadeh, X. Wang, F. Blaabjerg, J. Hjerrild, L. Kocewiaq, C. L. Bak, and B. Hesselbæk, “Couplings in phase domain impedance modeling of grid-connected converters,” IEEE Trans. Power Electron., vol. 31, no. 10, pp. 6792–6796, Oct. 2016.

[17] H. Nian, L. Chen, Y. Xu, H. Huang, and J. Ma, “Sequences domain impedance modeling of three-phase grid-connected converter using harmonic transfer matrices,” IEEE Trans. Energy Convers., vol. 33, no. 2, pp. 627–638, Jun. 2018.

[18] S. Gulur, V. M. Iyer, and S. Bhattacharya, “Stationary reference frame controller regulation and filter-based instability mitigation mechanism is clearly clarified. Conclusions can be drawn as follows:

1) The coupling-related instability is related to the design of the IP-CCI and also it is grid-impedance-dependent, so it is the consequence of interactions between the sequence-couplings and circuit-coupling;

2) Differently from the PLL-CCI, whose sequence-couplings just enlarge the frequency range of the negative damping. With no restrictions of the PLL, the IP-CCI has no negative damping regions in low-frequency range, but middle-frequency and high-frequency negative damping can be generated due to the strong couplings;

3) For the IP-CCI, the coupling-related instability can be removed by mitigation methods contributing to reduce the magnitude of the coupled-admittances at resonant frequencies as much as possible. For example, decreasing the resonant coefficient works for eliminating middle-frequency instabilities, decreasing the proportional coefficient helps to mitigate both middle- and high-frequency instabilities. Additionally, the extra filters are effective to ensure the stability of the IP-CCI in a wide frequency range.

REFERENCES

[1] J. Rocabet, A. Luna, F. Blaabjerg, and P. Rodriguez, “Control of power converters in AC microgrids,” IEEE Trans. Power Electron., vol. 27, no. 11, pp. 4734–4749, Nov. 2012.

[2] M. Ashabani and J. Jung, “Synchronous voltage controllers: Voltage-based emulation of synchronous machines for the integration of renewable energy sources,” IEEE Access, vol. 8, pp. 49497–49508, 2020.

[3] Y. Yu, H. Li, Z. Li, and Z. Zhao, “Modeling and analysis of resonance in LCL-type grid-connected inverters under different control schemes,” Energies, vol. 10, no. 1, p. 104, Jan. 2017.

[4] X. Wang and F. Blaabjerg, “Harmonic stability in power electronic-based power systems: Concept, modeling, and analysis,” IEEE Trans. Smart Grid, vol. 10, no. 3, pp. 2858–2870, May 2019.

[5] M. Liserre, R. Teodorescu, and F. Blaabjerg, “Stability of photovoltaic and wind turbine grid-connected inverters for a large set of grid impedance values,” IEEE Trans. Power Electron., vol. 21, no. 1, pp. 263–272, Jan. 2006.

[6] M. Cespedes, “Impedance modeling, analysis, and adaptation of grid-connected inverters with PLL,” Ph.D. dissertation, Dept. Elect. Eng., Rensselaer Polytech. Inst., Troy, NY, USA, 2014.

[7] Z. Xie, Y. Chen, W. Wu, Y. Xu, H. Wang, J. Guo, and A. Luo, “Modeling and control parameters design for grid-connected inverter system considering the effect of PLL and grid impedance,” IEEE Access, vol. 8, pp. 40474–40484, 2020.

[8] D. Dong, B. Wen, D. Boroyevich, P. Mattavelli, and Y. Xue, “Analysis of phase-locked loop low-frequency stability in three-phase grid-connected power converters considering impedance interactions,” IEEE Trans. Ind. Electron., vol. 62, no. 1, pp. 310–321, Jan. 2015.

[9] Z. Zhang, W. Wu, Z. Shuai, X. Wang, A. Luo, H. S.-H. Chung, and F. Blaabjerg, “Principle and robust impedance-based design of grid-tied inverter with LCL-filter under wide variation of grid-reactance,” IEEE Trans. Power Electron., vol. 34, no. 5, pp. 4362–4374, May 2019.

[10] S. Guler, V. M. Iyer, and S. Bhattacharya, “Stationary reference frame based current control structure with improved disturbance rejection for grid connected converters,” in Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC), San Antonio, TX, USA, Mar. 2018, pp. 1031–1035.

[11] J. G. Hwang, P. W. Lehn, and M. Winkelnkemper, “A generalized class of stationary frame-current controllers for grid-connected AC–DC converters,” IEEE Trans. Power Del., vol. 25, no. 4, pp. 2742–2751, Oct. 2010.

[12] Y. Gui, X. Wang, and F. Blaabjerg, “Vector current control derived from direct power control for grid-connected inverters,” IEEE Trans. Power Electron., vol. 34, no. 9, pp. 9224–9235, Sep. 2019.
XUEMEI ZHENG received the B.Eng. degree in electrical engineering, the M.Eng. degree in control engineering, and the Ph.D. degree in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 1992, 2000, and 2004, respectively. She is currently a Professor with the Department of Electrical Engineering, HIT. Her research interests include sliding mode control systems, wind power system control, smart-grid control, and energy management systems.

HAOYU LI (Member, IEEE) received the B.S. and M.S. degrees in electrical engineering, and the Ph.D. degree in control science and engineering from the Harbin Institute of Technology (HIT), Harbin, China, in 1995, 1997, and 2001, respectively. Since 2002, he has been with the Department of Electrical and Engineering, HIT, where he is currently a Professor and the Director of the Institute of Power Conversion and Control. From July 2014 to January 2015, he was a Visiting Professor with the New York State Center for Future Energy Systems, Rensselaer Polytechnic Institute. He has been engaged in the teaching and research in the field of power electronics with the HIT since 2002. His research interests include power conversion and control technology in harsh environment, modeling, analysis, and the design of high-efficiency high-power-density switched-mode power converters, including advanced control method and digital implementation. He has authored or coauthored more than 50 technical articles and held ten patents in China.

JINGHANG LU (Member, IEEE) received the B.Sc. degree in electrical engineering and the M.Sc. degree in electrical engineering from the Harbin Institute of Technology, China, in 2009 and 2011, respectively, and the M.Sc. degree in electrical engineering from the University of Alberta, Canada, in 2014, and the Ph.D. degree in power electronics from Aalborg University, Aalborg, Denmark, in 2018. From 2018 to 2019, he was a Research Fellow of Nanyang Technological University, Singapore. He is currently an Assistant Professor with the Harbin Institute of Technology (Shenzhen), Shenzhen, China. His research interests include uninterruptible power supply, microgrid, and the control of power converters.

* * *

JINGHANG LU (Member, IEEE) received the B.Sc. degree in electrical engineering and the M.Sc. degree in electrical engineering from the Harbin Institute of Technology, China, in 2009 and 2011, respectively, and the M.Sc. degree in electrical engineering from the University of Alberta, Canada, in 2014, and the Ph.D. degree in power electronics from Aalborg University, Aalborg, Denmark, in 2018. From 2018 to 2019, he was a Research Fellow of Nanyang Technological University, Singapore. He is currently an Assistant Professor with the Harbin Institute of Technology (Shenzhen), Shenzhen, China. His research interests include uninterruptible power supply, microgrid, and the control of power converters.

* * *