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A Modified DQ Impedance Model of Three-Phase Grid-Connected Inverter-Grid System Considering Coupling between Inverter and Grid

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Abstract—This paper presents a modified dq impedance model of the three-phase voltage source grid-connected inverter (GCI)-grid system considering coupling effect between GCI part and grid part for small-signal stability analysis. Steady-state terminal voltage and current information of the GCI part which are necessary in conventional dq impedance modelling methods are calculated based on grid parameters, i.e., grid voltage and grid impedance, and current references of current-controlled GCI or power references of power-controlled GCI. In addition, effects of dynamics of grid voltage and phase-locked loop (PLL) on dq impedance characteristics of grid part are also investigated, which enables the modified dq impedance model of grid part to relate with that of GCI part. The modified dq impedance model of the GCI part which takes the effects of grid voltage and grid impedance into account need not know steady-state terminal voltage and current information. In addition, the modified dq impedance model of grid part may provide accurate stability analysis during grid voltage changes. The insight of instability mechanism of the GCI-grid coupling system may be facilitated using the modified dq impedance models. Simulation results are given to validate correctness of the proposed dq impedance model of the GCI-grid system, and effectiveness of the dq impedance model for stability analysis.

Index Terms—Coupling effect, dq impedance model, grid-connected inverter, grid dynamics, stability analysis, terminal voltage.

I. INTRODUCTION

Recently, renewable energies, such as wind power and solar power, have been increasingly penetrating into existing utility grid. Voltage source grid-connected inverters (GCIs), as important interfaces, are widely used to transmit the generated electricity into utility grid [1]. However, instability phenomena can be triggered in various frequency ranges when undesired impedance interaction between GCIs and weak grid happens [2]–[4]. Impedance-based stability analysis methods for three-phase AC systems have been proposed to investigate the oscillation mechanism [5], where the key step is to establish efficient impedance models of GCI part and grid part [6].

As for the impedance modelling of GCI part, phasor-domain, sequence-domain and dq-domain impedance models have recently been developed [3], [7]–[14]. Frequency coupling and non-linearity phenomena cannot be captured by phasor-domain impedance model [4], [7]. In addition, modelling procedure of sequence impedance model is relatively complicated [11], [12]. On the contrary, non-linearity of the GCI, e.g., power control loop and phase-locked loop (PLL), can be captured by dq impedance model, and its derivation procedure is relatively simple [3]. It’s also found that the sequence-domain impedance model can be obtained by applying simple matrix transformation on the dq-domain impedance model [15]–[17]. Therefore, dq-domain impedance model is superior to the other two impedance models from the perspective of accuracy and complicity, and has been widely used for stability assessment of power electronics-dominated power systems [3], [13], [14], [18].

The dq impedance model of a GCI which consists of outer power control loop, inner current control loop and PLL is derived in [3]. It’s found that the dq impedance model is influenced by operation points, e.g., duty cycle, dq axles currents and terminal voltage magnitude. At steady state, duty cycle and dq axles currents of the power-controlled GCI are dependent on terminal voltage which is usually obtained by running power flow [19]. However, only when the power system is stable, simulation results of the power flow are accurate. In addition, the procedure is time consuming [19]. On the other hand, terminal voltage of the GCI is dependent on grid parameters, i.e., grid voltage and grid impedance [20]–[23]. It means that the dq impedance model of the GCI may be represented by grid parameters, and power flow can be avoided. In addition, the grid parameters-dependent dq impedance model of the GCI may facilitate understanding and revealing the instability mechanism of GCI-grid coupling system. Recently, the sequence-domain impedance model of the GCI considering the effects of grid impedance and frequency coupling is presented in [24], which shows that the modified sequence-domain impedance is able to provide accurate stability analysis compared with the conventional
impedance models which ignore the effects of grid impedance and frequency coupling. Similarly, a single-frequency output impedance model of the single-phase GCI which is derived based on the multi-frequency principle is developed in [25], which is able to capture the effects of grid impedance and frequency coupling of the PLL. However, the effects of GCI part on grid part impedance are not investigated in [24], [25].

As for impedance modelling of grid part, conventional impedance modelling method assumes that its small-signal model is not affected by GCI part and grid voltage dynamics [3]. The dq impedance model can easily be calculated by performing basic circuit series and parallel operations on grid components, i.e., grid resistance, inductance and capacitance [3]. However, in [22], it’s shown that the small-signal model of grid part is affected by PLL parameters and operating point. The control model of wind power plants and transmission line electromagnetic dynamics are combined in a linear model. And system stability is assessed by the open loop transfer function of the linear system model [22]. The small-signal modelling method of grid part paves a path to establish the dq impedance model of grid part considering PLL dynamics and operating point.

In this paper, the modified dq impedance models of GCI-grid coupling system under both power control mode and current control mode are presented. As for GCI part, terminal voltage and current of the GCI are calculated based on grid parameters, i.e., grid resistance and grid impedance, and current/power references. Therefore, calculation of operating point is not needed. In addition, grid dynamics can be reflected in the modified GCI impedance model, which is able to better understand how grid parameters influence dq impedance characteristics of the GCI. As for grid part, an operation point and grid voltage-dependent dq impedance model is established, which can be more accurate than the conventional grid impedance modelling method.

The rest of this paper is organized as follows. In Section II, the small-signal model of the GCI part is established, based on which the modified dq impedance model of GCI part is derived. The small-signal model of the grid part is established, based on which the modified dq impedance model of grid part is presented in Section III. In Section IV, simulation verification is performed. Finally, conclusions are drawn in Section V.

II. MODIFIED DQ IMPEDANCE MODEL OF GCI PART

In this section, existing dq impedance models of the GCI part are first reviewed, followed by explanation of the modified dq impedance models.

A. EXISTING DQ IMPEDANCE MODEL OF GCI PART

Fig. 1 shows the equivalent circuit model of single GCI connected with weak grid. The GCI is under vector control in dq reference frame, where d axis is aligned with the voltage vector at point of common coupling (PCC), as shown in Fig. 2(a). The control system commonly consists of outer power control loop, inner current control loop and PLL, of which

\[
\frac{1}{2} V_{dc} \Delta D_s = \overline{V}_s = Z_f \Delta I_s + \overline{V}^{\text{PCC}}_s \tag{3}
\]

where \( \overline{V}_m = V_{m,d} + jV_{m,q}, \overline{V}^{\text{PCC}}_s = V^{\text{PCC},d} + jV^{\text{PCC},q} = V_{\text{PCC}}, \overline{Z}_f = R_f + jX_f \). Fig. 3 shows the phasor diagrams of \( \Delta D_s \), \( \overline{V}_m \), \( \overline{I}_s \) and \( \overline{V}^{\text{PCC}}_s \).
For the GCI under current control mode, $D_d^s$ and $D_q^s$ can be calculated based on (3), shown as follows.

$$D_d^s = \frac{V_{PCC}}{0.5V_{dc}} + \frac{I_{g,d}^ref R_f - I_{g,q}^ref \overline{X_f}}{0.5V_{dc}}$$

$$D_q^s = \frac{I_{g,d}^ref \overline{X_f} + I_{g,q}^ref R_f}{0.5V_{dc}}$$  

(4)

It can be seen from (4) that when $I_{g,d}^ref$ and $I_{g,q}^ref$ are given, $D_d^s$ and $D_q^s$ are only dependent on $V_{PCC}$ and filter parameters, i.e., $R_f$ and $X_f$.

For the GCI under power control mode, $P_{ref}$ and $Q_{ref}$ can be calculated as follows.

$$P_{ref} = V_{PCC}^2 I_{g,d}^s + V_{PCC}^2 I_{g,q}^s = V_{PCC} I_{g,d}^s$$

$$Q_{ref} = V_{PCC}^2 I_{g,q}^s - V_{PCC}^2 I_{g,q}^s = V_{PCC} I_{g,q}^s$$  

(5)

$I_{g,d}^s$ and $I_{g,q}^s$ can then be calculated as follows.

$$I_{g,d}^s = \frac{P_{ref}}{V_{PCC}}$$

$$I_{g,q}^s = \frac{Q_{ref}}{V_{PCC}}$$  

(6)

On the other hand, by substituting (6) into (4), $D_d^s$ and $D_q^s$ can be calculated as follows.

$$D_d^s = \frac{V_{PCC}}{0.5V_{dc}} + \frac{P_{ref} R_f - Q_{ref} \overline{X_f}}{0.5V_{dc} V_{PCC}}$$

$$D_q^s = \frac{P_{ref} \overline{X_f} + Q_{ref} R_f}{0.5V_{dc} V_{PCC}}$$  

(7)

By applying the Ohms’ law on grid impedance $R_g$ and $L_g$, voltage vector at PCC $\overrightarrow{v}_{PCC}$ can be calculated as follows.

$$\overrightarrow{v}_{PCC} = v_{g}^s + jv_{g,q}^s = \overrightarrow{T_{Δsg}} v_g^s + \overrightarrow{Z_g} \overrightarrow{T_{Lsg}}$$  

(8)

where $\overrightarrow{T_{PCC}} = v_{PCC,d}^s + jv_{PCC,q}^s = v_{PCC}, \overrightarrow{v}_g^s = v_{g,d}^s + jv_{g,q}^s, \overrightarrow{Z_g} = R_g + jX_g, \overrightarrow{T_{Δsg}} = (\Delta \overrightarrow{v}_{PCC} - \Delta \overrightarrow{v}_{PCC} - \Delta \overrightarrow{v}_{PCC})$, and $

\overrightarrow{T_{Lsg}}"
It can be derived from (11) that
\[
V_{PCC}^4 + (2X_g Q_{ref} - 2R_g P_{ref} - V_g^2)V_{PCC}^2 + (R_g^2 + X_g^2)(P_{ref}^2 + Q_{ref}^2) = 0 \tag{12}
\]

Solving (12), \( V_{PCC} \) can be expressed by \( P_{ref}, Q_{ref} \) and grid parameters, shown as (13) at the top of the next page. It can be seen from (6), (7) and (12) that the unknown three grid parameters, shown as (13) at the top of the next page.

By comparing (15) and (19), it can be seen that when grid voltage dynamic is further considered, additional one component is added to \( \Delta v_{PCC,d}^s \) and \( \Delta v_{PCC,q}^s \), respectively. Note that when \( V_g = 0 \), (15) and (19) can be related by
\[
\begin{align*}
\Delta v_{PCC,d1}^s &= \Delta v_{PCC,q1}^s = \Delta v_{PCC,d1}^s + j \Delta v_{PCC,q1}^s = \Delta v_{PCC,d1}^s + j \Delta v_{PCC,q1}^s \\
\Delta v_{PCC,q2}^s &= \Delta v_{PCC,q1}^s + j \Delta v_{PCC,d1}^s \\
&= \Delta v_{PCC,d1}^s + j \Delta v_{PCC,q1}^s
\end{align*}
\tag{21}
\]
i.e.,
\[
\left[ \begin{array}{c}
\Delta v_{PCC,d1}^s \\
\Delta v_{PCC,q1}^s \\
\Delta v_{PCC,q2}^s
\end{array} \right] = Z_g^{-1} G_{grid}^i \left[ \begin{array}{c}
\Delta v_{PCC,d2}^s \\
\Delta v_{PCC,q2}^s
\end{array} \right] \tag{24}
\]
where \( G_{grid}^i \) is defined as follows.
\[
G_{grid}^i = \frac{1}{AB - 1} \begin{bmatrix} AB & B \\ A & AB \end{bmatrix} \tag{25}
\]

By comparing (15) and (19), it can be seen that when grid voltage dynamic is further considered, additional one component is added to \( \Delta v_{PCC,d}^s \) and \( \Delta v_{PCC,q}^s \), respectively. Note that when \( V_g = 0 \), (15) and (19) can be related by
\[
\begin{align*}
\Delta v_{PCC,d2}^s &= \Delta v_{PCC,q1}^s = \Delta v_{PCC,d1}^s + j \Delta v_{PCC,q1}^s \\
\Delta v_{PCC,q2}^s &= \Delta v_{PCC,q1}^s + j \Delta v_{PCC,d1}^s \\
&= \Delta v_{PCC,d1}^s + j \Delta v_{PCC,q1}^s
\end{align*}
\tag{21}
\]
i.e.,
\[
\left[ \begin{array}{c}
\Delta v_{PCC,d1}^s \\
\Delta v_{PCC,q1}^s \\
\Delta v_{PCC,q2}^s
\end{array} \right] = Z_g^{-1} G_{grid}^i \left[ \begin{array}{c}
\Delta v_{PCC,d2}^s \\
\Delta v_{PCC,q2}^s
\end{array} \right] \tag{24}
\]
where \( G_{grid}^i \) is defined as follows.
\[
G_{grid}^i = \frac{1}{AB - 1} \begin{bmatrix} AB & B \\ A & AB \end{bmatrix} \tag{25}
\]

It can be seen from (16) and (24) that additional transfer function matrix \( G_{grid}^i \) is added when grid voltage dynamic is further considered. Therefore, \( G_{grid}^i \) can depict the effect of grid voltage dynamics on small-signal relationship between \( \Delta v_{PCC} \) and \( \Delta i_g \). Note that the dq impedance model of the grid part is not symmetrical anymore when further considering grid voltage dynamics (A 2×2 matrix is symmetrical if the two diagonal components are the same, and the two off-diagonal components are opposite.).

The small-signal model of grid part in Fig. 1 can then be established, as shown in the red dotted box in Fig. 2(b).

C. Dynamics of Grid Voltage and PLL Considered

In this case, \( v_g^\ast \neq 0 \) and \( T_{\Delta sc}^2 \neq 1 \). In addition, all parameters are represented in grid reference frame. (8) is rewritten as follows.
\[
\begin{align*}
v_{PCC,d}^s &= V_g \cos(\Delta sg) + R_g i_{g,d}^s + L_g \frac{di_{g,d}^s}{dt} - \omega_L i_{g,q}^s \\
v_{PCC,q}^s &= -V_g \sin(\Delta sg) + \omega_L i_{g,q}^s + R_g i_{g,q}^s + L_g \frac{di_{g,q}^s}{dt} \tag{18}
\end{align*}
\]
The steady-state solution of (18) is shown as (10) which can be perturbed and linearized as follows.
\[
\begin{align*}
\Delta v_{PCC,d2}^s &= R_g \Delta i_{g,d}^s - X_g \Delta i_{g,q}^s - \frac{(X_g \Delta i_{g,d}^s + R_g \Delta i_{g,q}^s)}{A} \\
\Delta v_{PCC,q2}^s &= R_g \Delta i_{g,q}^s + X_g \Delta i_{g,d}^s + \frac{X_g \Delta i_{g,q}^s - R_g \Delta i_{g,d}^s}{B} \tag{19}
\end{align*}
\]

where
\[
A = \sqrt{\frac{V_g^2}{X_g i_{g,d}^s + R_g i_{g,q}^s}^2 - 1}
\]
\[
B = \sqrt{\frac{V_{PCC}^2}{V_{PCC}^2 + R_g i_{g,d}^s + X_g i_{g,q}^s}^2 - 1} \tag{20}
\]
\[ V_{PCC} = \sqrt{R_g P_{ref} - X_g Q_{ref} - \frac{\sqrt{V_g^4 + 4(R_g P_{ref} - X_g Q_{ref})V_g^2 - 4(X_g P_{ref} + Q_{ref} R_g)^2}}{2}} + \frac{V_g^2}{2} \]  

\( \Delta s c \) can be ignored. By comparing the real parts and imaginary parts of both sides of (27), \( \Delta v_{PCC,d3} \) and \( \Delta v_{PCC,q3} \) can be obtained as follows.

\[
\Delta v_{PCC,d3} = R_g \Delta i_{g,d} - X_g \Delta i_{g,q} - (R_g i_{g,d} + X_g i_{g,q}) \Delta^2 g c
\]

\[
\Delta v_{PCC,q3} = R_g \Delta i_{g,q} + X_g \Delta i_{g,d} + (R_g i_{g,q} - X_g i_{g,d}) \Delta^2 g c
\]

\[-V_{PCC} \Delta^2 g s \]  

(28)

On the other hand, \( \Delta^2 g c \) can be represented as follows [22],

\[
\Delta^2 g c = \frac{G_{PLL}(X_g \Delta i_{g,d} + R_g \Delta i_{g,q})}{V_{PCC} + (X_g i_{g,d} - R_g i_{g,q}) G_{PLL}}
\]

(29)

where

\[
G_{PLL} = \frac{K_{pPLL} + K_{iPLL}}{s^2 + K_{pPLL} s + K_{iPLL}}
\]

(30)

where \( K_{pPLL} \) and \( K_{iPLL} \) are the proportional and integral coefficients of the PLL controller. \( G_{PLL} \) is the transfer function from \( \Delta^2 g s \) to \( \Delta^2 g c \) [22], i.e.,

\[
\Delta^2 g s = \frac{\Delta^2 g c}{G_{PLL}}
\]

(31)

Then, it can be seen from (19) and (28) that by ignoring PLL dynamics, i.e., \( G_{PLL} = 1 \) and \( \Delta i_{g,d} = \Delta i_{g} \), \( \Delta v_{PCC,d2} \) is the same as \( \Delta v_{PCC,d3} \). Similar with (24), (28) can also be expressed in matrix form by substituting (29) and (31) into (28).

To further illustrate the coupling relationship between the GCI part and the grid part, coupling paths are shown in Fig. 5(a). The current or power generated by the GCI part enforces the terminal voltage to change due to the dynamics of the grid part. The changed terminal voltage further influences the dq impedance characteristics of the GCI part via PLL or power control loop. On the other hand, as shown in Section III-C, the dq impedance model of the grid part is affected by terminal voltage variation due to the PLL and grid voltage characteristics.

Based on the established small-signal model of the whole system in Fig. 2, system impedance model in dq-domain can be established, as shown in Fig. 5(b), where \( Z_{s\text{-modi}}(V_g, R_g, L_g) \) indicates that the dq impedance model of the GCI part is dependent on grid parameters. \( Z_{g\text{-modi}}(V_g) \) indicates that the dq impedance model of the grid part is dependent on grid voltage \( V_g \).

IV. SIMULATION VERIFICATION

In this section, the correctness of the established dq impedance models of GCI part and grid part is verified by simulation results in Matlab/Simulink. Furthermore, the effectiveness of the established dq impedance models for stability analysis is also shown.

A. Verification of Correctness of the Modified DQ Impedance Model of GCI Part

1) Impacts of \( X_g, i_{g,d}(P_{ref}), i_{g,q}(Q_{ref}) \) on \( V_{PCC} \): Table I shows the circuit and controller parameters of the GCI in Fig. 2(a). To simplify the verification procedure, only the GCI under current control mode is considered here, whereas the theoretical analysis of the GCI under power control mode can also be performed in a similar way.

### TABLE I CIRCUIT AND CONTROLLER PARAMETERS OF THE GCI IN FIG. 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-link voltage ( V_{dc} )</td>
<td>1150 V</td>
</tr>
<tr>
<td>Grid fundamental frequency ( f_1 )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Filter inductance ( L_f )</td>
<td>263 ( \mu )H</td>
</tr>
<tr>
<td>Filter resistance ( R_f )</td>
<td>0</td>
</tr>
<tr>
<td>Switching frequency ( f_{swit} )</td>
<td>2.5 kHz</td>
</tr>
<tr>
<td>Sampling frequency ( f_{samp} )</td>
<td>2.5 kHz</td>
</tr>
<tr>
<td>Grid Vrms (phase-to-phase) ( V_g )</td>
<td>575 V</td>
</tr>
<tr>
<td>Proportional gain of power controller ( k_{pPQ} )</td>
<td>0.00050549</td>
</tr>
<tr>
<td>Integral gain of power controller ( k_{iPQ} )</td>
<td>0.03294</td>
</tr>
<tr>
<td>Proportional gain of current controller ( k_{pI} )</td>
<td>0.00050549</td>
</tr>
<tr>
<td>Integral gain of current controller ( k_{iI} )</td>
<td>0.3294</td>
</tr>
<tr>
<td>Proportional gain of PLL ( K_{pPLL} )</td>
<td>8</td>
</tr>
<tr>
<td>Integral gain of PLL ( K_{iPLL} )</td>
<td>32</td>
</tr>
</tbody>
</table>
Fig. 6 shows the simulation results of $V_{PCC}$ and $\Delta sg$ with $L_g$ varying from 0 to 14 mH with step size 1 mH, i.e., $X_g = \omega_1 L_g$ varies from 0 to 4.396 $\Omega$, when $R_g = 0$, $I_{g,d}^{ref} = 100$ A and $I_{g,q}^{ref} = 0$. In addition, the theoretical $V_{PCC}$ and $\Delta sg$ can be calculated by (10), i.e., $V_{PCC} = \sqrt{V_g^2 - (X_g I_{g,d}^{ref})^2}$ and $\Delta sg = \cos^{-1}\left(\frac{469.49^2 - (31400 L_g)^2}{469.49\sqrt{469.49^2 - (31400 L_g)^2}}\right)$, which are also plotted in Figs. 6(a), (b). It can be seen that the simulation results highly agree with the theoretical analysis results when $L_g$ is smaller than 9 mH, which validates the correctness of theoretical analysis results in (10). The counter-intuitive phenomenon that $V_{PCC}$ decreases and $\Delta sg$ increases as $X_g$ increases actually results from the PCC voltage-based vector control [23]. If the GCI is under grid voltage-based vector control, the increment of $X_g$ should lead to an increment of $V_{PCC}$. Note that the simulation results are not accurate when $L_g$ is larger than 8 mH, since the system becomes unstable under weak grid condition. It means that steady-state point acquisition method based on power flow simulation is not applicable when the grid is weak.

Fig. 7 shows the simulation results of $V_{PCC}$ and $\Delta sg$ with $I_{g,d}^{ref}$ varying from 100 A to 800 A with step size 100 A when $R_g = 0$, $L_g = 2$ mH and $I_{g,q}^{ref} = 0$. In addition, the theoretical $V_{PCC}$ and $\Delta sg$ can be calculated by (10), i.e., $V_{PCC} = \sqrt{V_g^2 - (X_g I_{g,d}^{ref})^2}$ and $\Delta sg = \cos^{-1}\left(\frac{469.49^2 - (0.628I_{g,d}^{ref})^2}{469.49\sqrt{469.49^2 - (0.628I_{g,d}^{ref})^2}}\right)$, which are also plotted in Figs. 7(a), (b). It can be seen that the simulation results highly agree with the theoretical analysis results, which validates the correctness of theoretical analysis results in (10). It can also be seen that $V_{PCC}$ decreases and $\Delta sg$ increases as $I_{g,d}^{ref}$ increases. Similar with Fig. 6, the counter-intuitive phenomenon also results from the PCC voltage-based vector control. In addition, high active power level makes the system unstable, and simulation results are not accurate anymore.

Fig. 8 shows the simulation results of $V_{PCC}$ with $I_{g,q}^{ref}$ varying from -400 A to 400 A when $R_g = 0$, $L_g = 2$ mH and $I_{g,d}^{ref} = 100$ A. In addition, the theoretical $V_{PCC}$ can be calculated by (10), i.e., $V_{PCC} = \sqrt{V_g^2 - (X_g I_{g,q}^{ref})^2} = \sqrt{469.49^2 - (31400 L_g)^2}$, which also plotted in Figs. 8(a), (b). It can be seen that the simulation results highly agree with the theoretical analysis results, which validates the correctness of theoretical analysis results in (10). Note that when under current control mode, reactive power injection does not influence system stability, whereas the system stability will be influenced under power control mode [14].

2) Impact of $X_g$ on $Z_{qq,dq}$: Since $Z_{qq}$ of the dq impedance model plays an important role in low-frequency stability assessment, Fig. 9 shows the Bode diagram of $Z_{qq}$ component with $L_g$ varying from 0 mH to 14 mH with step size 2 mH when $R_g = 0$, $I_{g,d}^{ref} = 100$ A and $I_{g,q}^{ref} = 0$. It can be seen that low-frequency impedance characteristic is influenced by grid impedance. Specifically, Fig. 9(b) shows that phase angle in low-frequency range increases as $L_g$ increases.

B. Influence of GCI Part on the Modified DQ Impedance Model of Grid Part

Fig. 10 shows the calculation results of $\frac{1}{A}$ and $\frac{1}{B}$ with $L_g$ varying from 0 to 20 mH with step size 1 mH when $R_g = 0$, $I_{g,d}^{ref} = 100$ A and $I_{g,q}^{ref} = 0$ using (20), i.e., $\frac{1}{A} = \frac{1}{\sqrt{469.49^2 - (31400 L_g)^2}}$ and $\frac{1}{B} = \frac{1}{\sqrt{469.49^2 - (31400 L_g)^2}}$. It can be seen that $\frac{1}{A}$ and $\frac{1}{B}$ are zero when $L_g$ exceeds a certain threshold value. We can derive from (16) and (23) that under
weak grid condition, the modified dq impedance model of the grid part can be simplified as the conventional dq impedance model.

Fig. 11 shows the calculation results of \( \frac{1}{A} \) and \( \frac{1}{B} \) with \( I_{g,d}^{ref} \) varying from 0 to 800 A when \( R_g = 0 \), \( L_g = 2 \) mH and \( I_{g,q}^{ref} = 0 \) using (20), i.e., \( \frac{1}{A} = \sqrt{\frac{1}{0.628I_{g,d}^{ref}}} \) and \( \frac{1}{B} = \sqrt{\frac{1}{469.49 - (0.628I_{g,d}^{ref})^2}} \). It can be seen that \( \frac{1}{A} \) increases as \( I_{g,d}^{ref} \) decreases from 0 A to 750 A, and decreases as \( I_{g,d}^{ref} \) increases from 750 A to 800 A. In addition, \( \frac{1}{B} \) decreases to zero quickly as \( I_{g,d}^{ref} \) increases. No that both \( \frac{1}{A} \) and \( \frac{1}{B} \) are zero when enough high active current is injected.

Similarly, Fig. 12 shows the calculation results of \( \frac{1}{A} \) and \( \frac{1}{B} \) with \( I_{g,q}^{ref} \) varying from -400 A to 400 A when \( R_g = 0 \), \( L_g = 2 \) mH and \( I_{g,d}^{ref} = 100 \) A using (20), i.e., \( \frac{1}{A} = \sqrt{\frac{1}{0.628I_{g,q}^{ref}}} \) and \( \frac{1}{B} = \sqrt{\frac{1}{469.49 - (0.628I_{g,q}^{ref})^2}} \). It can be seen that both \( \frac{1}{A} \) and \( \frac{1}{B} \) are constant.

C. Verification of Effectiveness of the Modified DQ Impedance Model of the GCI-Grid Coupling System for Stability Analysis

Fig. 13 shows the Bode plots of the theoretically-derived dq impedance models of GCI part using the proposed model \( Z_{g\text{-modi}} \) and measured impedance frequency responses \( Z_{g\text{-mea}} \). It can be seen that the \( Z_{g\text{-modi}} \) highly agrees with \( Z_{g\text{-mea}} \). In addition, Bode diagrams of the theoretically-derived dq impedance models of grid part using the proposed model and measured impedance frequency responses of three grid conditions, i.e., case 1: \( L_g = 2 \) mH and \( C_g = 60 \) \( \mu \)F, case 2: \( L_g = 5 \) mH and \( C_g = 150 \) \( \mu \)F, and case 3: \( L_g = 13 \) mH and \( C_g = 390 \) \( \mu \)F, are also plotted in Fig. 13. It can be seen that high-frequency oscillation happens at 47 Hz (572-100=472 Hz) under case 1. System is stable under case 2. Low-frequency oscillation happens at 68 Hz and 32 Hz (50+18=68 Hz and 50-18=32 Hz) under case 1.

Figs. 14-16 show time-domain simulation results of grid current and corresponding frequency spectrum under the three grid conditions, which agree with the Bode plots in Fig. 13. The simulation results verifies the effectiveness of the proposed dq impedance modelling method of the GCI-grid coupling system for stability analysis.

V. CONCLUSION

This paper presents novel dq impedance models of GCI part and grid part for stability analysis. As for the dq impedance model of GCI part, steady-state operation point, e.g., duty cycle, dq axes currents and terminal voltage is not required. Instead, grid parameters, i.e., grid impedance and grid voltage.
are included in the modified dq impedance model of the GCI part. The proposed dq impedance modelling method of GCI need not run power flow to obtain steady-state operating point, which may be not practical for unstable system. As for the impedance model of grid part, conventional dq impedance model is modified to consider the effects of dynamics of grid voltage and PLL. Measured dq impedance models using frequency scanning method highly agree with the modified dq impedance models of GCI part and grid part, indicating the correctness of the proposed impedance modelling method. In addition, system stability characteristics can be predicted by the modified system dq impedance model. The proposed dq impedance model of the whole system may provide more insights to reveal the oscillation mechanism than the conventional dq impedance model where GCI part and grid part are modelled independently.

REFERENCES