Abstract—In this paper, a generalized closed-loop control (GCC) scheme is proposed for voltage source converters (VSCs) with LC or LCL output filters. The proposed GCC scheme has a single-loop control of inverter output (voltage or current) and two parallel virtual impedance terms using additional measurements. The virtual impedance can be the equivalent internal impedance or external impedance (or both), depending on their control term and feedback variable selection. The internal impedance term is mainly responsible for providing desired damping to the filter circuit, and the external virtual impedance term can effectively adjust the converter system closed-loop output impedance. As each term in the GCC scheme can be controlled independently, the proposed GCC scheme has great flexibility and can easily realize and explain the performances of the traditional single- and multiloop control schemes and their different variations. Moreover, the GCC scheme provides a distinct physical meaning of each control term, which makes the control parameter tuning more straightforward and robust. Additionally, as shown in this paper, the proposed GCC scheme can tackle some traditionally challenging control objectives by avoiding the harmonics filtering or derivative terms. Experimental results from laboratory VSC prototypes are obtained to validate the proposed GCC scheme.

Index Terms—Active damping, generalized closed-loop control (GCC), LC filter, LCL filter, multiloop control, single-loop control, virtual impedance, voltage source converter (VSC).

I. INTRODUCTION

Voltage source converters (VSCs) have been widely used in various kinds of power conversion applications, such as active power filters (APF) [1]–[3], [24]–[26], distributed generations (DG) [4]–[6], [20]–[23], [27], variable speed drives [6], [7], and uninterruptible power supplies (UPSs) [9], [20], [21], [29], [30]. In these applications, LC or LCL output filters are usually adopted to mitigate the converter switching ripples. However, if the converters are not properly controlled, inherent resonances of the filters can introduce serious power quality and stability problems. To deal with the filter resonances, both passive damping and active damping methods have been implemented [8], [13], [15], [16], [20], [26]. As the active damping suppresses the resonances without introducing additional losses on the filter [20], it is increasingly adopted to improve the VSC system performance.

A VSC system with LC or LCL filter is shown in Fig. 1, where the filter is placed between the converter output and loads/grid. Typically, if the filter capacitor voltage is controlled directly, such as in a UPS system or a voltage-controlled DG system [21], [22], [28], the LC filters are normally adopted. On the other hand, LCL filters are more widely used in current-controlled grid-connected converters such as APFs, active rectifiers, and current-controlled DG systems. However, with LCL filters, the capacitor voltage can also be controlled [32], [34]. In this case, the grid side inductor \( L_2 \) is usually treated as a part of the feeder impedance. For the closed-loop current or voltage control of a VSC system, both single- and multiloop control schemes have been developed. Generally, the simple single-loop control is subject to the tradeoff between control dynamics and steady-state performance. In addition, it is sensitive to grid background noises [10], [11]. As more feedback becomes available for VSC with high-order filters, various kinds of multiloop controllers are often implemented [9], [18], [19], [28]–[31]. The multiloop control inherently provides damping effects to the VSC system and can therefore tackle the limitations of the conventional single-loop control. However, the inner loop feedback variable selection and the multiloop controller parameter design are not straightforward.

For the multiloop controller parameter tuning, one approach is to assume that the dynamics of the inner loop are much faster than the outer loop [29]. As a result, outer and inner control loops are decoupled and their parameters can be tuned through an iterative process [31]. However, this iterative method is complicated.
and the outer and inner loop parameters cannot be determined together. Alternatively, an interesting design method through pole-zero cancellation is reported in [19]. In this method, high-order outer loop controller is simplified as a proportional–integral (PI) controller during the parameter design stage. Therefore, accurate effects of the outer loop controller can hardly be examined. In [14], a two-step approach is proposed to first design the outer loop PI controller based on a simplified filter plant (equivalent single inductor filter). Then, the inner loop control term is tuned based on the open-loop transfer functions to maintain system stability. In this method, as the damping performance is examined after the design of the outer loop controller, the system might be sensitive to filter resonances if the outer loop PI controller is not designed properly. For multiloop controllers, the selection of inner loop control feedback is also important. Some analysis of the system performance regarding different feedback variables based on the closed-loop transfer functions can be found in [9]. However, what essentially causes the performance differences has not been understood in a more intuitive way. A more straightforward evaluation of different inner loop feedback variables with distinct physical meanings would be much desirable.

Another way to improve the VSC system control performance is through the virtual impedance concept [2], [3], [15], [16], [20]–[22], [28]. The virtual impedance can be categorized into two types: 1) the virtual impedance for the active damping of filter resonances [15], [16], [20]; and 2) the virtual impedance external to a VSC system closed-loop equivalent circuit, such as the virtual output series impedance of voltage-controlled DG units in a voltage-governed microgrid [21], [22], [28], and the virtual parallel resistance of a current-controlled resistive-APFs (R-APF) [2], [3] that proposed to improve the stability and power quality of distribution systems. These two types of virtual impedance are referred to as internal virtual impedance and external virtual impedance, respectively, in this paper. The internal virtual impedance is realized by modifying the pulsewidth modulation (PWM) reference signals directly, similar to the inner control loop of a multiloop control scheme [15], [20]. On the other hand, the external impedance is realized by modifying the VSC control reference [2], [3], [21], [22]. Through modifying the control reference, the external impedance control dynamics are therefore limited by the VSC closed-loop control bandwidth. For the external virtual impedance implementation, a major challenge is the implementation method, as the derivative operation and harmonic detection may be involved.

To address the closed-loop control challenges of a VSC system with LC or LCL filters, this paper proposes a generalized closed-loop control (GCC) strategy, which incorporates the VSC closed-loop control term, the internal virtual impedance term, and the external virtual impedance term into a parallel control structure. Unlike the conventional cascaded multiloop control, the effects of the virtual internal impedance term is to add a virtual damping impedance to the original filter circuit, which ensures a well-damped filter plant at first. Therefore, the closed-loop term in GCC can provide a superior tracking control based on the modified filter plant. In addition, with distinct meaning of the internal impedance term, the feedback variable selection

![Fig. 2. Proposed GCC scheme. (a) Voltage-controlled VSC with LC filter. (b) Current-controlled VSC with LCL filter.](image-url)
However, unlike the traditional double-loop control, the internal impedance control term in the proposed GCC scheme can be more flexibly tuned as the gains of \( H_G(s) \) and \( H_{\text{internal}}(s) \) are regulated separately without having the constraint of \( H_G(s) = G_{\text{outer}}(s)G_{\text{inner}}(s) \) as in the double-loop control scheme. Furthermore, the performance variation of a double-loop controlled system with different inner loop feedbacks [9] can also be explained by examining the positions and values of their corresponding internal virtual impedance in the GCC schemes. More details on this are presented in Section III.

Similarly, the double-loop current control of a grid-connected VSC with LCL filter is shown in Fig. 3(b), where the outer loop feedback is the line current, and the inner loop feedback is the capacitor current or converter-side current. By carrying out the analysis in a similar way, it can be seen that the double-loop current control of a VSC with LCL filter is able to be represented by the GCC scheme using a single-loop control and an additional internal impedance, as shown in the following:

\[
V_{\text{PWM}}^{*} = G_{\text{outer}}(s)G_{\text{inner}}(s)(I_{\text{ref}} - I_2) - G_{\text{inner}}(s)I_{\text{inner}} \\
= H_G(s)(I_{\text{ref}} - I_2) - H_{\text{internal}}(s)I_{\text{inner}}
\]

where \( I_{\text{ref}} \) and \( I_2 \) are the reference current and feedback line current, respectively. Similarly, the closed-loop control performance difference with different inner loop feedbacks is related to the position and value of the internal virtual impedance.

In addition, the proposed GCC scheme can also be used to investigate the performance of many other control schemes in a similar way. For instance, the recently proposed weighted average current control scheme (WAC) for VSC with LCL filter system in [17] measured the combination of inverter and line currents with a predetermined weighting factor. This control scheme can be expressed as follows:

\[
V_{\text{PWM}}^{*} = G_{\text{outer}}(s)(I_{\text{ref}} - (\beta I_2 + (1 - \beta) I_1))
\]

where the weighting factor \( \beta \) is determined by the inductance ratio at converter and grid side, \( G_{\text{outer}}(s) \) is the proportional plus resonant (PR) controller in stationary frame. Considering that the converter current equals the sum of line current and capacitor current as shown in (7), (8) can then be obtained through simple manipulation

\[
I_1 = I_2 + I_C
\]

\[
V_{\text{PWM}}^{*} = G_{\text{outer}}(s)(I_{\text{ref}} - I_2) - G_{\text{outer}}(s)(1 - \beta) I_C.
\]

As illustrated, the improved performance of single-loop controller in (6) (compared to the traditional single-loop control) can be explained by using the proposed GCC controller in (8), where the equivalent internal impedance control term becomes \( H_{\text{internal}}(s) = G_{\text{outer}}(s)(1 - \beta) \) with the feedback variable being the capacitor current. With this internal impedance, damping of the LC or LCL resonance can be obtained.

Further discussion of this internal impedance and its damping effects will be presented in Section III.
C. External Virtual Impedance

When a voltage-controlled VSC + LC filter system is connected to a low voltage grid, the external virtual reactance \( Z_{EV}(s) \) can be placed in series with the resistive feeders to make the equivalent line impedance inductive with improved system stability and transient performance [22], [28]. In this case, the reference voltage \( V_{ref} \) (for the closed-loop control) needs to be updated by considering the voltage drops at the external virtual impedance

\[
V_{\text{ref,new}} = V_{\text{ref}} - Z_{EV}(s)I_2
\]

where \( I_2 \) is the line current.

When the external virtual impedance is implemented in the double-loop control scheme in Fig. 3(a), the control form can be obtained by incorporating (9) into (4) as follows:

\[
V_{PWM} = H_G(s) (V_{\text{ref,new}} - V_C) - H_{\text{internal}}(s)I_{\text{inner}}
\]

\[
= H_G(s) (V_{\text{ref}} - V_C) - H_{\text{internal}}(s)I_{\text{inner}}
\]

\[
- H_G(s)Z_{EV}(s)I_2.
\]

Comparing (10) to the GCC scheme in (1), we find that the external impedance realized above is equivalent to the GCC scheme with an external impedance control term of \( H_{\text{external}}(s) = H_G(s)Z_{EV}(s) \), where the line current is the external impedance feedback.

In addition, the current-controlled VSCs with LCL filters can be used in APFs. The APF can be the distributed APF system or the DG system with ancillary harmonics compensation functions. The multifunctional DG systems work as R-APFs when sufficient apparent power is available [2]. Accordingly, the VSC current reference is determined in the following:

\[
I_{\text{ref,new}} = I_{\text{ref}} + \left( \frac{H_{\text{HAR}}(s)V_{\text{grid}}}{Z_{EV}(s)} \right)
\]

where \( I_{\text{ref}} \) is the current reference for dc-link voltage control in an APF system or the fundamental power control reference in a DG system. Here \( Z_{EV}(s) \) is the external parallel virtual resistance and \( H_{\text{HAR}}(s) \) is the harmonic detector responsible for extracting harmonic components of grid voltage.

By replacing the current reference in (5) with the updated reference (11), the final control scheme becomes as follows:

\[
V_{PWM} = H_G(s) (I_{\text{ref,new}} - I_2) - G_{\text{internal}}(s)I_{\text{inner}}
\]

\[
= H_G(s) (I_{\text{ref}} - I_2) - G_{\text{internal}}(s)I_{\text{inner}}
\]

\[
- [H_G(s)H_{\text{HAR}}(s)/Z_{EV}(s)]V_{\text{grid}}.
\]

Equation (12) shows that the external parallel virtual resistance control in R-APF is actually the GCC scheme with \( H_{\text{external}}(s) = H_G(s)H_{\text{HAR}}(s)/Z_{EV}(s) \), with the grid voltage as the external impedance feedback. From the above discussion, it can be found that the implementation of external impedance term relies on the closed-loop controller \( H_G(s) \). Therefore, the bandwidth of the external impedance shall be sufficiently lower than the internal impedance.

III. FURTHER INVESTIGATION OF THE INTERNAL IMPEDANCE DAMPING EFFECTS

As discussed earlier, the internal virtual impedance in the GCC scheme helps to provide active damping to the VSC system. This function is similar to the virtual resistor active damping concept that addresses the resonance problems of LC and LCL filters [15], [16], [20]. Further considering that the internal impedance control term takes effect with an open-loop manner (without closed-loop control) and adjusts the PWM reference directly, its associated bandwidth will be high enough to address the LC or LCL filter resonance as long as the VSC switching frequency is sufficiently higher than the filter resonant frequency. To simplify the discussion here, the combined outputs of the closed-loop control term and the external impedance term in the GCC scheme are defined as \( V_{PWM,\text{R}} \) as follows:

\[
V_{PWM,\text{R}} = H_G(s) (C_{G,\text{ref}} - C_G) - H_{\text{external}}(s)C_{\text{external}}.
\]

Due to the limited bandwidths of the closed-loop and the external impedance terms, the internal impedance term \( H_{\text{internal}}(s)C_{\text{internal}} \) is considered to be the dominant term around the resonant frequency of filters. As a result, the system damping performance will be regulated by this term.

First, when the converter-side inductor current \( I_1 \) is selected as the internal term feedback, the effect of the internal impedance term is to introduce an additional voltage drop at the modulation voltage. Therefore, it equals to place a series internal virtual impedance \( Z_{V1}(s) = H_{\text{internal}}(s) \) at the converter-side inductor, as shown in Fig. 4(a) and (b). In this figure, the filter input voltage \( V_{PWM,\text{R}} \) is described in (13). It is obvious that if a proportional controller is used in \( H_{\text{internal}}(s) \), the internal impedance will be just a damping resistor. Moreover, with the proposed GCC scheme, complex impedances can also be realized by selecting the desired \( H_{\text{internal}}(s) \).

Alternatively, when the capacitor current is selected as the internal impedance feedback variable, its physical meaning is not obvious. This is because the modification of PWM voltage reference cannot be directly associated with the internal virtual circuit at the filter capacitor branch due to the presence of converter-side filter inductor. However, the effect of PWM...
voltage on the filter capacitor branch can be established indi-

citely. Without implementing the internal impedance control
term, the line/load harmonic current is determined as follows
(parasite resistors of filter inductors are neglected here):

$$I_2 = I_1 - I_c = -\left(sCV_C + \frac{V_C}{sL_1}\right). \quad (14)$$

When the internal impedance term is activated, the harmonic
current in (14) need to be modified, as shown in (15)

$$I_{2,IV} = I_{1,IV} - I_c = -\left(\frac{V_C - H_{\text{internal}}(s)I_C}{sL_1} + sCV_C\right)$$
$$= -\left(\frac{\frac{V_C}{sL_1} + sCV + \frac{H_{\text{internal}}(s)I_C}{sL_1}}{sL_1}\right). \quad (15)$$

From (15), it can be noticed that the internal active damping
brings an additional term to line/load current. The additional
current effects can be accurately modeled as an impedance in
parallel with the filter capacitor as follows:

$$Z_{IV}(s) = \frac{V_C}{(I_{2,IV} - I_2)} = \frac{sL_1V_C}{H_{\text{internal}}(s)I_C} = \frac{L_1}{C_f H_{\text{internal}}(s)}. \quad (16)$$

This equivalent internal impedance in parallel with the filter
capacitor is shown in Fig. 4(c) and (d).

Based on the aforementioned discussions, the physical mean-
ing of the internal impedance control terms with different feed-
backs is clarified. It also reveals that modeling the filter capacitor

current feedback control as a series impedance with filter capac-
ier [15], [16], [26] is not accurate as the effects of filter inductor
between the VSC and the filter capacitor is not considered.

Moreover, it can be shown that the WAC control shown in
(6) and (7) essentially introduces high-order parallel internal
virtual impedance at the filter capacitor branch. Considering
a PR controller $H_{PR}(s)$, as shown in (17), for WAC current
tracking

$$H_{PR}(s) = k_p + \frac{2k_1\omega_{\text{cut}}s}{s^2 + 2\omega_{\text{cut}}s + \omega_0^2} \quad (17)$$

where $k_p$ and $k_1$ are proportional and integral gains of con-
troller, and $\omega_{\text{cut}}$ and $\omega_0$ are the cutoff and fundamental frequen-
cies of the controller, respectively. The corresponding parallel
internal virtual impedance around filter resonant frequency can be obtained as follows:

$$Z_{IV}(s) = \frac{L_1}{C_f (1 - \beta) H_{PR}(s)} \approx \frac{L_1}{C_f (1 - \beta) (k_p s + k_1\omega_{\text{cut}})}. \quad (18)$$

As shown in Fig. 5, the high-order internal virtual impedance
of WAC control equals to put a high-pass filter at filter capa-
citor branch. At the frequency range above its cutoff frequency
($k_1\omega_{\text{cut}}/k_p$), it can be further simplified as a virtual resistance
$Z_{IV}(s) \approx L_1/C_f \cdot (1 - \beta) \cdot k_p$, which provides damping to the
VSC system. In [33], it is found that in a weak grid with large
grid inductance, the proportional gain $k_p$ needs to be increased to
maintain satisfied damping performance and wide control
bandwidth. This phenomenon can also be explained using the
developed virtual impedance in Fig. 5, where the weak grid con-
dition represents a large ratio $\beta$. This will significantly degrade

the effects of damping resistance ($L_1/C_f \cdot (1 - \beta) \cdot k_p$). How-
ever, the large proportional gain $k_p$ can compensate the effects
of weak grid. Also, a large $k_p$ decreases the cutoff frequency
of the high-pass virtual damping impedance in (18). Therefore,
large control bandwidth in WAC control can be realized.

IV. ANALYSIS AND DESIGN OF GCC CONTROL PARAMETERS

With distinct physical meanings of the control terms in
the GCC scheme, the parameter tuning process will be more
straightforward. Here a current-controlled VSC with LCL filter
is presented as an example. It is worth mentioning that the pro-
posed parameter design method can also be directly applied to
the tuning of multiloop control due to the equivalence of mul-
tiloop control to the GCC scheme, as discussed in the previous
section.

Note that the external impedance term is not considered in this
section as the design of external impedance is mainly determined
by VSC–microgrid interaction requirements.

A. Design of GCC Control Parameters

With the proposed GCC scheme, the control parameter tuning
can be simplified as into the following two steps.

1) Design of the Internal Virtual Impedance $H_{\text{internal}}(s)$:
For the current-controlled VSC with an LCL filter, the modified
filter plant in Fig. 4(b) and (d) can be described as follows:

$$I_2 = G_1(s) V_{PWM,R} - G_2(s) V_{\text{grid}} \quad (19)$$

where $V_{PWM,R}$ is defined in (13). When the inductor current $I_1$
is selected as the internal impedance feedback variable, $G_1(s)$
and $G_2(s)$ can be expressed as follows:

$$G_1(s) = \frac{Z_2(s)}{(Z_1(s) + Z_{IV}(s)) (Z_2(s) + Z_3(s)) + Z_2(s)Z_3(s)} \quad (20)$$

$$G_2(s) = \frac{Z_1(s) + Z_{IV}(s) + Z_2(s)}{(Z_1(s) + Z_{IV}(s)) (Z_2(s) + Z_3(s)) + Z_2(s)Z_3(s)} \quad (21)$$

\[Fig. 5. \quad \text{Internal virtual impedance with WAC control.}\]
where $Z_1(s) = L_1s + R_1$, $Z_2(s) = 1/(C_fs)$, and $Z_3(s) = L_2s + R_2$. $Z_{IV}(s) = H_{\text{internal}}(s)$ is the internal impedance connected in series with inductor $L_1$.

It can be seen from Fig. 6 that $G_2(s)$ contains a significant resonance peak with original filter plant, and the resonance peak can be damped by the internal impedance term. However, if a large internal impedance term (such as $H_{\text{internal}}(s) \approx 100$) is added to the plant, an additional resonance can be introduced. This can be explained by the derived equivalent circuit in Fig. 4(b), where a large virtual impedance will block the left side of the LCL filter. Therefore, when the grid voltage is polluted, an additional LC resonance might be introduced between $C_f$ and $L_2$. On the other hand, a large internal impedance term also decreases the magnitude of $G_1(s)$ in the low frequency range, as shown in Fig. 7. When there is a step change of reference current, the dynamic tracking performance will inevitably be affected. With the aforementioned considerations, if the inductor current internal impedance term is desired, a moderate internal impedance term $Z_{IV}(s) = 25$ can be selected. Note that the current-controlled VSC system discussed here is selected to be the same as that in the experiments. The associated parameters are shown in Table I.

Similarly, when capacitor current $I_c$ is chosen as the internal impedance feedback, the relationship in (19) is still valid. However, $G_1(s)$ and $G_2(s)$ need to be modified accordingly, as shown (22) and (23), at the bottom of this page, where $Z_{IV}(s)$ is the parallel internal impedance in the LCL filter capacitor branch, as illustrated in (16).

Unlike the inductor current internal impedance, when the capacitor current is considered, the filter resonance peak in $G_2(s)$ is effectively dampened (see Fig. 8). There is no obvious additional LC resonance even if a large damping gain is selected for $H_{\text{internal}}(s)$. However, when the LCL filter is over-damped by a large damping gain $H_{\text{internal}}(s)$, it is equivalent to adding a small parallel impedance at the capacitor branch. Considering that the small impedance essentially provides a path for grid voltage harmonics, the modified filter plant might be sensitive to low-order harmonics (such as 2nd) in this situation.

Further looking into Fig. 9 reveals that the magnitude of $G_1(s)$ in this case is significantly larger than its inductor current counterpart. This means that the line current has better response to converter-side PWM voltage. Therefore, the capacitor current internal impedance gives better dynamics performance.

$$
G_1(s) = \frac{Z_{2}(s)Z_{IV}(s)}{Z_2(s)Z_3(s)Z_{IV}(s) + Z_1(s)Z_3(s)Z_{IV}(s) + Z_1(s)Z_2(s)Z_{IV}(s) + Z_1(s)Z_2(s)Z_3(s)}
$$

$$
G_2(s) = \frac{Z_2(s)Z_{IV}(s) + Z_1(s)Z_{IV}(s) + Z_1(s)Z_2(s)}{Z_2(s)Z_3(s)Z_{IV}(s) + Z_1(s)Z_3(s)Z_{IV}(s) + Z_1(s)Z_2(s)Z_{IV}(s) + Z_1(s)Z_2(s)Z_3(s)}
$$

**TABLE I**

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<tr>
<th>3-phase VSC+LC filter</th>
<th>VALUE</th>
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<tbody>
<tr>
<td>LC filter</td>
<td>$L_1 = 4 \text{ mH}$, $C_f = 40 \mu\text{F}$</td>
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<tr>
<td>Inductive feeder</td>
<td>$L_2 = 2.5 \text{ mH}$, $R_2 = 0.2 \Omega$</td>
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<td>DC Link voltage</td>
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<tr>
<td>DC Link capacitor</td>
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<tr>
<td>Switching frequency</td>
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<tr>
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<td>Nonlinear load</td>
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</tr>
<tr>
<td>DC Link voltage</td>
<td>260V</td>
</tr>
<tr>
<td>DC Link capacitor</td>
<td>2000 $\mu$F</td>
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<tr>
<td>Switching frequency</td>
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<td>Grid feeder</td>
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<td>DC Link capacitor</td>
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<tr>
<td>External impedance</td>
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</table>
this paper, the appropriate \( H_{\text{internal}}(s) \) is selected to be 25 for capacitor current internal impedance.

2) Design of Closed-Loop Tracking Term \( H_G(s) \): After getting the dampened filter plant, the closed-loop controller \( H_G(s) \) can be designed based on the simplified filter plant in [14]. Note that when the inductor current is used as the internal impedance term, the equivalent effect of the modified filter plant is close to a resistor (see the zero phase angle around line frequency in Fig. 7). As a result, conventional assumption in [14] that LCL filter can be simplified as a single equivalent inductor at line frequency is not valid in this case.

Compared to the two-step method in [14], the proposed approach here provides a well-damped LC or LCL filter model at first, and then the closed-loop control term will be designed based on the dampened model. It therefore guarantees a robust system performance with sufficient damping.

Note that although the current-controlled VSC with LCL filter is considered here, the proposed analysis method can also be applied to the voltage controlled VSC with the LC filter. Similar conclusions can also be found in voltage-controlled system. For instance, when large internal virtual resistance (with inductor current feedback) blocks the path of inductor in LC filter plant, additional resonance can also be introduced by the interaction among the filter capacitor and the inductive feeder impedance [see Fig. 4(a)]. This phenomenon is actually consistent with the finding in [34], where a large bandwidth of the inner loop controller can adversely introduce resonances in a parallel-connected UPS system. In addition, if the internal impedance with the capacitor current feedback is implemented with a large proportional gain, the equivalent small parallel impedance will provide a path for the harmonic load current, which reduces the distortion of capacitor voltage (with reduced stability margin). These conclusions will be further validated by experiments.

B. Closed-Loop Transfer Function Confirmation

To validate the GCC parameter design and analysis method, the Norton’s equivalent circuit of VSC + LCL system with GCC is obtained, as shown in Fig. 10. Considering that the filter damping and voltage/current tracking performances are mainly related to \( H_{\text{internal}}(s) \) and \( H_G(s) \), the external impedance is not considered at this stage. Therefore, the resulting PWM voltage in (13) is further simplified as follows:

\[
V_{\text{PWM} \rightarrow R} = \frac{1}{1 + \frac{G_1(s)H_G(s)}{G_2(s)}} V_{\text{grid}}
\]

where \( K_{\text{C, out}}(s) \) is the current tracking coefficient and \( Y_{\text{out}}(s) \) is the parallel admittance. When a PR controller, as shown in (17), is considered for \( H_G(s) \) in (25), the Bode plots of current tracking coefficient and parallel admittance in (25) with different internal impedance terms are shown in Figs. 11–14.

Figs. 11 and 12 show the closed-loop tracking gain and parallel admittance with the inductor current feedback internal impedance term. These conclusions will be further validated by experiments.
impedance. Consistent with the previous analysis, an additional resonance appears with large internal impedance gain; this series resonance frequency caused by the capacitor and the grid-side inductor can be roughly obtained as $1/2\pi \sqrt{C_L I_2}$.

Figs. 13 and 14 demonstrate the tracking gain and parallel admittance with the capacitor current feedback internal impedance. In contrast to Figs. 11 and 12, the tracking gain has better response around fundamental frequency in this case. As mentioned earlier, the system becomes more sensitive to low-order harmonics if the modified filter plant is over damped. This conclusion is further proven here by the Bode plots in Fig. 14, where the 2nd harmonic is amplified with a large internal impedance term (such as $H_{\text{internal}} = 100$).

V. EXTERNAL VIRTUAL IMPEDANCE IMPLEMENTATION EXAMPLE

Unlike the design of $H_{\text{internal}}(s)$ and $H_G(s)$, where the parameters are mainly related to filter parameters and VSC system control requirements, the design of external impedance is usually considered at distribution system level. Therefore, the external impedance in the GCC scheme is focused on implementation techniques. In this section, a voltage-controlled VSC with external virtual inductor, as illustrated in Fig. 15, is considered as a case study, where the closed-loop coefficient gain $K_{V,\text{out}}(s)$ and the original series impedance $Z_{\text{out}}(s)$ are associated with $H_{\text{internal}}(s)$ and $H_G(s)$. For the external impedance implementation, using GCC scheme enables the reduction of the phase/magnitude error caused by the high-/low-pass filter and the noise amplification in conventional schemes [21], [22]. In addition, the GCC scheme is computationally effective, which requires no complex load current harmonic detection algorithm.

The expression of the external impedance term with voltage-controlled VSC can be derived from (10) as follows:

$$H_{\text{external}}(s)I_2 = Z_{\text{EV}}(s)H_G(s)I_2$$

(26)

where $Z_{\text{EV}}(s)$ is the desired external virtual impedance. This combination of the external virtual impedance and the closed-loop controller $H_G(s)$ is very useful to tackle some traditional challenges in the virtual impedance control. For example, when the virtual external impedance takes effect at the harmonics, harmonic PR controllers in (27) can be considered for $H_G(s)$ as follows:

$$H_G(s) = k_P + \sum_j \frac{2k_{f,j} \omega_{\text{cut}} s}{s^2 + 2\omega_{\text{cut}} s + \omega_j^2}$$

(27)

where $k_{f,j}$ and $\omega_j$ are the integral gains and frequencies at fundamental and harmonics.

If a virtual reactance $sL_V$ is considered as $Z_{\text{EV}}(s)$, the external impedance term will be expressed as follows:

$$Z_{\text{EV}}(s)H_G(s)I_2 = \left(k_P + \sum_j \frac{2k_{f,j} \omega_{\text{cut}} s}{s^2 + 2\omega_{\text{cut}} s + \omega_j^2}\right)sL_V I_2$$

$$= \left(k_P L_V s + \sum_j \frac{2k_{f,j} L_V \omega_{\text{cut}} s^2}{s^2 + 2\omega_{\text{cut}} s + \omega_j^2}\right)I_2$$

(28)

where the derivative term $k_P L_V s$ may cause high-frequency noise amplifications. However, this can be avoided by selecting $k_P$ in (28) to be zero. This is very reasonable as the proportional
Fig. 16 shows the traditional external virtual impedance implementation scheme, where the virtual impedance realization is accomplished through the modification of the reference voltage \( V_{\text{ref,new}} = V_{\text{ref}} - Z_{EV}(s) \cdot I_2 \). The derivative term of inductor voltage drop emulation can be replaced by a high-pass filter to avoid the noise amplification, which leads to steady-state phase and magnitude errors [28].

Fig. 17 shows the virtual output impedance implementation using the proposed GCC scheme. Compared to the traditional control scheme to realize the external virtual impedance, the effects of output virtual impedance are directly added to the VSC PWM voltage reference. Fig. 18 shows the Bode plot of the closed-loop external virtual impedance in Fig. 17, where it can be seen that both the magnitude and phase angle of the implemented virtual inductance are very close to the physical impedance at the selected frequencies.

Note that with the external impedance term, the inductance \( L_V \) at the fundamental and each selected harmonic frequencies are not necessarily to the same. However, for the conventional implementation method in Fig. 16, this frequency-varying inductance can only be achieved using additional complex harmonic extractors.

\[
H_{\text{external}}(s)I_2 = \sum_j \frac{2k_{l,j}L_V\omega_{\text{cut}}s^2}{s^2 + 2\omega_{\text{cut}}s + \omega_j^2} I_2.
\] (29)
large internal impedance term \( H_{\text{internal}}(s) = 75 \). In this situation, the LC filter inductor branch is blocked by virtual internal impedance and there appears significant resonance between the filter capacitor and the inductive line. As a result, the voltage THD in this case is 34.66%.

When the same proportional gain \( H_{\text{internal}}(s) = 25 \) is considered for the virtual impedance with capacitor current feedback, as the internal parallel virtual resistance at filter capacitor branch can suppress the resonance, the quality of voltage in Fig. 21 (THD = 6.61%) is better than its inductor current counterpart shown in Fig. 19. In contrast to the inductor current feedback in Fig. 20, a large gain \( H_{\text{internal}}(s) = 70 \) with capacitor current will further attenuate the harmonic of voltages, as shown in Fig. 22, where the voltage THD is reduced to 5.01% even if there is only fundamental resonant controller in \( H_G(s) \).

The experimental results from a three-phase current-controlled grid-connected VSC + LCL filter system are shown from Figs. 23–25. In this experiment, 0.4% 11th and 1% 2nd harmonics are added to the grid voltage \( V_{\text{grid}} \), and there is no harmonic resonant controller in \( H_G(s) \). As shown in Fig. 23, when a large inductor current internal impedance term is adopted \( H_{\text{internal}}(s) = 75 \), the line current is distorted (THD = 5.58%). Consistent with the derived Bode plots, a large series virtual resistor with \( L_1 \) blocks the converter-side filter circuit, and the system becomes sensitive to the resonance between the filter capacitor and grid-side inductor.

The performance of the system with large capacitor current internal impedance term \( H_{\text{internal}}(s) = 110 \) is obtained in Fig. 24. Since large internal impedance gain represents a small parallel virtual damping impedance at capacitor branch, the 11th harmonic current disappears while the low-order harmonics (2nd harmonic current) is amplified. Here the 2nd harmonic current is 27.5%. In addition, an improved line current (THD = 4.51%) can be found in Fig. 25 when an appropriate internal impedance with \( H_{\text{internal}}(s) = 25 \) is adopted.

Finally, to investigate the performance of the proposed external virtual impedance implementation method, a single-phase voltage-controlled grid-connected VSC + LC filter system is employed. The system configuration is illustrated in Fig. 26, where a nonlinear load is connected to the VSC and the grid with identical line impedance \( Z_{\text{line}} \) (0.55 mH, 0.2 Ω). Here the power reference of DG unit is set to provide a half of the load demand. Since the grid feeder and DG feeder have identical impedance, the harmonic currents shall also be equally shared by the DG and the grid when external virtual impedance is not
TABLE II
HARMONIC ANALYSIS

<table>
<thead>
<tr>
<th></th>
<th>3rd harmonics</th>
<th>5th harmonics</th>
<th>7th harmonics</th>
<th>9th harmonics</th>
<th>11th harmonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG current (Fig. 27(b))</td>
<td>67.95%</td>
<td>36.57%</td>
<td>7.44%</td>
<td>6.67%</td>
<td>1.62%</td>
</tr>
<tr>
<td>Grid current (Fig. 27(c))</td>
<td>79.61%</td>
<td>33.27%</td>
<td>5.44%</td>
<td>4.16%</td>
<td>1.35%</td>
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<tr>
<td>DG current (Fig. 28(b))</td>
<td>36.29%</td>
<td>13.68%</td>
<td>1.38%</td>
<td>3.13%</td>
<td>0.69%</td>
</tr>
<tr>
<td>Grid current (Fig. 28(c))</td>
<td>102.72%</td>
<td>48.18%</td>
<td>6.50%</td>
<td>4.33%</td>
<td>1.14%</td>
</tr>
</tbody>
</table>

Fig. 26. Equivalent circuit of voltage-controlled VSC + LC filter system with external virtual impedance $Z_{EV}(s)$.

Fig. 27. Performances without external virtual impedance. (a) $V_{\text{grid}}$ (100 V/d). (b) $I_2$ (5 A/d). (c) $I_{\text{grid}}$ (5 A/d).

Fig. 28. Performances with 2.5 mH external virtual impedance at the fundamental, 5th, 7th, 9th, and 11th harmonics. (a) $V_{\text{grid}}$ (100 V/d). (b) $I_2$ (5 A/d). (c) $I_{\text{grid}}$ (5 A/d).

activated. Fig. 27 shows the grid current $I_{\text{grid}}$ (THD = 86.63%) and line current $I_2$ (THD = 79.25%) of the system without external virtual impedance.

When an external virtual inductance (2.5 mH, takes effect at fundamental, 3rd, 5th, 7th, 9th, and 11th harmonics) is produced in the VSC + LC filter system, more harmonic currents are pushed to the grid, as shown in Fig. 28. Accordingly, the quality of line current is improved with a THD of 39.54%. At the same time, the grid current THD increases to 114.58%. Table II gives the harmonic analysis of the system with/without the external impedance. It can be seen that the harmonic currents at the selected frequencies are shared according to DG and grid impedance ratios.

VII. CONCLUSION

This paper proposed a novel GCC scheme with embedded internal and external virtual impedance terms. Selective functions of the proposed GCC scheme are discussed. By providing a distinct physical meaning of the internal impedance term, the stability and the damping of VSC system with GCC scheme and many conventional controllers can be investigated. Moreover, the parameter tuning in the GCC scheme is more intuitive and flexible compared to the conventional approaches. This paper also shows that the GCC scheme is superior to conventional controllers in controlling external impedance by avoiding the harmonic filtering and derivative terms. Finally, experimental results on both voltage-controlled VSC systems with output LC filters and current-controlled VSC systems with output LCL filters are provided to validate the proposed GCC scheme.

REFERENCES


