Investigation of Active Damping Approaches for PI-based Current Control of Grid-Connected PWM Converters with LCL Filters

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Abstract—This paper deals with different active damping approaches for PI-based current control of grid-connected PWM converters with LCL filters which are based on one additional feedback. Filter capacitor current as well as voltage feedback for purpose of resonance damping are analyzed and compared. Basic studies in continuous Laplace domain show that either proportional current feedback or derivative voltage feedback yield resonance damping. Detailed investigations of these two approaches in discrete z-domain taking into account the discrete nature of control implementation, sampling, and PWM are carried out. Several ratios of LCL resonance frequency and control frequency are considered. For high resonance frequencies only current feedback stabilizes the system. For medium resonance frequencies both approaches show good performance. For low resonance frequencies stability gets worse even if voltage feedback offers slightly better damping properties. Measurement results validate the theoretical results.

I. INTRODUCTION

Three-phase grid-connected PWM converters are often used in regenerative energy systems and in adjustable speed drives when regenerative braking is required [1]. Power regeneration, adjustable power factor, controllable DC-link voltage, and less line current harmonic distortion are the most important advantages with respect to passive diode bridges. For reduction of line current ripple LCL filters are often used as grid filters [2]. Due to high efficiency and flexibility active resonance damping solutions as part of the converter control attracted much attention [3]–[8].

The converter control commonly consists of an outer DC-link voltage PI control and inner current control loops. For some applications with line current feedback the well-known PI control in synchronous reference frame can be employed. But the inner PI-based current control is not suitable for many applications in dependence of the ratio of LCL-resonance frequency and control frequency [9]. For lower ratios or converter current feedback PI control leads to instability. For these applications active resonance damping gets integrated into the current control loop. Sensorless resonance damping [10] as well as damping with an additional feedback are presented in literature. In [3], [4], [10], and [11] resonance is damped with additional feedback of the voltages across the filter capacitors. In [12] and [13] the current through the filter capacitors is used for resonance damping and in [7] different solutions based on so-called virtual resistors are presented. For certain system settings the resonance damping effect is put into evidence and the control performance is analyzed. Analyses with different system settings, especially different ratios of resonance and control frequency, are often not carried out. For this reason one damping approach presented in [7] is analyzed in more detail in [14].

In this paper a more general analysis of different resonance damping solutions is carried out. Basic LCL-resonance damping properties of different feedback states are studied. Feedback of the current through or voltage across the LCL filter capacitors with different feedback transfer functions are taken into consideration and compared in continuous Laplace domain. The results show how the different feedback signals need to be fed back in order to achieve resonance damping. Detailed investigation of two most suitable damping approaches in discrete z-domain taking into account the discrete nature of control implementation, sampling, and PWM follows the general analyses. Different ratios of LCL filter resonance and control frequency are analyzed. By that limitations of the approaches based on one additional feedback of the current through or voltage across the filter capacitors are shown.

First the system is described and mathematical model is shown in section II and a control overview is given in III. Basic study of damping properties is carried out in section IV. Detailed investigation of filter capacitor current feedback with different typical system settings is presented in section V-A and filter capacitor voltage feedback in section V-B. Measurement results are shown in section VI. Finally, a conclusion is given.

II. SYSTEM DESCRIPTION

A three-phase IGBT voltage source converter is studied. It is connected to the grid via LCL filter as shown in Fig. 1. In addition to the DC link voltage and converter currents either
the filter capacitor currents or filter capacitor voltages are measured. The line voltages are measured for the purpose of synchronizing the control with the line voltage. The converter is loaded by an inverter-fed induction machine. In this paper different filter capacitances are used in order to study different ratios of resonance and control frequency.

Applying Kirchhoff's laws yields the continuous model of the LCL filter ($u_C$: converter output voltage) [9]:

\[
\begin{align*}
\frac{d}{dt} i_L &= \frac{1}{L_{fg}} \left( u_{dc} - u_C - j\omega i_L \right) \\
\frac{d}{dt} i_f &= \frac{1}{L_{fc}} \left( u_{dc} - u_C - j\omega i_f \right) \\
\frac{d}{dt} i_C &= \frac{1}{C_f} \left( i_L - i_f \right) - j\omega \cdot u_{dc} \\
\end{align*}
\]

The resonance frequency of the LCL filter can be calculated:

\[
\omega_{Res} = \sqrt{\frac{L_{fg} + L_{fc}}{C_f L_{fg} L_{fc}}} 
\]

Because the outer DC-link voltage is outside the scope of this paper, the reader is referred to [9] for the mathematical description of the DC-link dynamics and its control. From (1) the transfer function $G_{LCL}^{Ucf}(s)$ can be derived

\[
G_{LCL}^{Ucf}(s) = \frac{U_{cf}(s)}{U_C(s)} = \frac{1}{L_c C_f} \frac{1}{s^2 + \omega^2_{Res}} 
\]

and taking into account, that $I_{cf}(s) = s C_f U_{cf}(s)$ holds, gives

\[
G_{LCL}^{Icf}(s) = \frac{I_{cf}(s)}{I_C(s)} = \frac{U_{cf}(s)}{U_C(s)} = \frac{1}{s} \frac{s}{s^2 + \omega^2_{Res}} 
\]

III. CONTROL OVERVIEW

The control structure is shown in Fig. 2. The DC-link voltage is controlled with PI controller [9]. Active and reactive converter currents are controlled in synchronous reference frame with PI controllers. In this paper converter current control is focused on. Similar analyses can be carried out with line current control. PI controllers are tuned with symmetrical optimum [15] whereas the L filter approximation of the LCL filter is used [16]:

\[
k_p = \frac{-L_{fg} + L_{fc}}{3 \cdot T_c} ; \quad T_I = 9 \cdot T_c
\]

With this PI tuning and backwards implementation [17] the reference step response shows an overshoot of approx. 30% and the reference is crossed after approx. 3-4 control periods. Note that more stringent requirements with respect to overshoot could be fulfilled by different tuning. Additionally, a feed forward decoupling is used [9]. For the LCL filter system active resonance damping is required. Sensorless resonance damping is possible [18], but it has been shown to be rather sensitive to parameter variations [8]. Moreover, its application is not possible for every kind of LCL filter design [9]. Additional feedback of system states offers improvements. Various solutions can be found in literature. In this paper a more generic study of approaches to damp resonance with feedback of one additional system state is carried out.

IV. BASIC STUDY OF RESONANCE DAMPING WITH DIFFERENT FEEDBACK STATES

As the resonance is caused by the filter capacitors it is reasonable to use the current through or voltage across them for the purpose of resonance damping. It depends strongly on the application and voltage as well as current level which kind of sensor to chose. For higher power/current levels (MW range, but still low voltage $< 1000$ V AC) current sensors are much more expensive than voltage sensors. At low power (few kW range) standard current sensors might even be cheaper than voltage sensors with the same insulation level. In the lowest power/current range, where the power circuit typically is integrated on a PCB, other issues (such as use of PCB area) might be important cost drivers. Moreover, in some applications voltage sensors are used anyway for grid synchronization [3]. The number of sensors can also be reduced by estimation of feedback signals [19]. In this paper resonance damping properties of both feedback states are studied.

The influence of filter capacitor current or voltage feedback on the system poles is studied separately. The analysis is carried...
Fig. 4. Impact of different continuous feedback characteristics on the system pole-zero locations in continuous s-plane (PWM neglected): Filter capacitor voltage feedback (top) and filter capacitor current feedback (bottom).

out in continuous Laplace domain. For this purpose delays caused by PWM and computation as well as discretization effects are neglected at this stage. More detailed analyses are presented later in section V. The loops illustrated in Fig. 2 are analyzed whereas different feedback transfer functions $K(s)$ are taken into consideration, namely proportional, derivative, and integrative feedback. The closed-loop transfer function $G_c(s)$ can be calculated:

$$G_c(s) = \frac{G_{LCL}(s)}{K(s) + G_{LCL}(s)}$$

whereas for $U_{Cf}$ feedback (3) is used and (4) for $I_{Cf}$ feedback.

In this paper feedback on the voltage references is considered. Note, that feedback on the current references instead of voltage references is possible as well. This can be beneficial with respect to current overshoot during transients [6]. In [7] and [14] it is used within the so-called concept of virtual resistor. In [6] it is used as part of deadbeat state space control. Similar analyses including the PI-controller in the loop give the required feedback types. As this is beyond the scope of this paper results are not shown here.

A. Filter capacitor voltage feedback

Evaluations of (6) with (3) for various feedback types are shown in Tab. I. For proportional feedback the transfer function of a resonator is obtained whereas the natural resonance frequency $\omega_{Res}$ is shifted in dependence of $K$. As can be seen in Fig. 4 the complex conjugated poles are shifted along the imaginary axis in dependence of the proportional gain. Thus no resonance damping is achieved by proportional feedback of the filter capacitor voltage.

Derivative feedback gives a second order delay transfer function. The natural resonance frequency $\omega_{Res}$ is kept but a non-zero damping factor is achieved which is the term related to $s$. The complex conjugated poles are shifted into the left s-plane in dependence of the derivative gain. Thus resonance damping is achieved by derivative feedback of the filter capacitor voltage without frequency shift.

From Fig. 4 it can be seen that the system poles are shifted into the right s-half plane for integrative feedback type. Thus the system gets unstable for integrative feedback.

It can be concluded that derivative filter capacitor voltage feedback is required for resonance damping. Approaches in literature using the filter capacitor voltage for resonance damping basically follow this result. In [3] and [10] the voltage is fed back with a lead element that exhibits high pass characteristics. In [4] a high pass filter is directly selected from the start.
TABLE I
CLOSED-LOOP TRANSFER FUNCTIONS WITH $U_{CF}$ AND $I_{CF}$ FEEDBACK FOR DIFFERENT FEEDBACK TYPES

<table>
<thead>
<tr>
<th>Feedback type</th>
<th>$G_c(s)$ for $U_{CF}$ feedback</th>
<th>$G_c(s)$ for $I_{CF}$ feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K(s) = K$ (P-type)</td>
<td>$\frac{1}{LcCf} \frac{s^2 + (\omega^2_{Res} + K/(LcCf))}{s^2 + (\omega^2_{Res} + K/(LcCf))}$</td>
<td>$\frac{1}{Lc} \frac{s^2 + s(K_{CF}/(Lc) + \omega^2_{Res})}{s^2 + (K_{CF}/(Lc) + \omega^2_{Res})}$</td>
</tr>
<tr>
<td>$K(s) = Ks$ (D-type)</td>
<td>$\frac{1}{LcCf} \frac{s^2 + s(K_{CF}/(LcCf)) + \omega^2_{Res}}{s^2 + s(K_{CF}/(LcCf)) + \omega^2_{Res}}$</td>
<td>$\frac{1}{Lc} \frac{s^2 + s(K_{CF}/(Lc) + \omega^2_{Res})}{s^2 + (K_{CF}/(Lc) + \omega^2_{Res})}$</td>
</tr>
<tr>
<td>$K(s) = \frac{K}{s}$ (I-type)</td>
<td>$\frac{1}{LcCf} \frac{s^2 + s\omega^2_{Res} + K/(LcCf)}{s^2 + s\omega^2_{Res} + K/(LcCf)}$</td>
<td>$\frac{1}{Lc} \frac{s^2 + s(K_{CF}/(Lc) + \omega^2_{Res})}{s^2 + (K_{CF}/(Lc) + \omega^2_{Res})}$</td>
</tr>
</tbody>
</table>

B. Filter capacitor current feedback

Based on the result of the previous section it can be expected that proportional $I_{CF}$ feedback yields resonance damping, as $I_{CF}(s) = sCfUCf(s)$ holds. The pole zero maps in Fig. 4 and the transfer functions in Tab. I confirm that expectation. Approaches in literature using the filter capacitor current for resonance damping, follow this result. In [12] [13] proportional feedback is used.

V. DETAILED ANALYSIS OF OVERALL DIGITAL CURRENT CONTROL SYSTEM

For the following detailed study a typical system setting of a medium power drive is selected, see Tab. II. In order to cover a typical range of LCL filter parameters three different LCL filter settings are studied. The choice of filter elements is a trade-off between switching harmonics attenuation, reactive power consumption, relative short circuit voltage drop, grid decoupling, filter losses as well as costs and size of filter elements. Research on LCL filter design is documented in [16], [20]. From control and resonance damping points of view the ratio of resonance frequency to control frequency is most important. Therefore the control is analyzed in detail for three characteristic ratios. In this paper the control frequency is kept constant and the resonance frequency is varied by changing the filter capacitance. The inductances are not changed. Table III shows the LCL filter parameter settings selected for the following analyses. Settings are classified into high, medium, and low resonance frequency. The results can easily be transferred to other LCL filter settings and switching frequencies.

From the previous basic study it is clear that proportional filter capacitor current feedback and derivative filter capacitor voltage feedback gives resonance damping. Its discrete realization on a microprocessor-based system gives some additional challenges that are to be considered. Moreover, the overall current control system needs to be studied as active resonance damping directly influences the current dynamic. The model used for system analysis is shown in Fig. 5. Taking the sampling process into account leads to the analysis in discrete z-domain. The continuous LCL filter model is discretized by zero order hold [17]. Moreover, parasitic series resistances of the inductors are taken into account but parallel resistances modeling core losses are neglected. It is worth noting that in practice they give some natural resonance damping [9]. The coupling terms in (1) are neglected and the analysis is done for one axis only. The fundamental PI controller in its backwards switching principle gives resonance damping. Its discrete realiza-

![Fig. 5. Detailed current control structure: PI control with resonance damping by feedback of $U_{CF}$ or $I_{CF}$.

TABLE II
SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_L$</td>
<td>Line voltage (phase-to-phase, rms)</td>
<td>400 V</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Line angular frequency</td>
<td>2π 50 Hz</td>
</tr>
<tr>
<td>$U_{DC}$</td>
<td>DC-link voltage</td>
<td>700 V</td>
</tr>
<tr>
<td>$P$</td>
<td>Nominal power (grid-side)</td>
<td>25 kW</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Switching/ control frequency</td>
<td>2.5 / 5kHz</td>
</tr>
<tr>
<td>$C_{DC}$</td>
<td>DC link capacitance</td>
<td>2710 μF</td>
</tr>
</tbody>
</table>

TABLE III
LCL FILTER SETTINGS AND CORRESPONDING RESONANCE FREQUENCIES

<table>
<thead>
<tr>
<th>Setting</th>
<th>$C_f$/μF (p.u.)</th>
<th>$L_{f_b}$/mH (p.u.)</th>
<th>$R_{f_b}$/mΩ (p.u.)</th>
<th>$f_{Res}$/kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>16.3 (3.25 %)</td>
<td>0.75 (3.7 %)</td>
<td>0.9 (0.9 %)</td>
<td>1.69 (high)</td>
</tr>
<tr>
<td>II</td>
<td>32.6 (6.5 %)</td>
<td>0.75 (3.7 %)</td>
<td>0.9 (0.9 %)</td>
<td>1.19 (medium)</td>
</tr>
<tr>
<td>III</td>
<td>97.8 (19.5 %)</td>
<td>0.75 (3.7 %)</td>
<td>0.9 (0.9 %)</td>
<td>0.69 (low)</td>
</tr>
</tbody>
</table>

$L_{f_b}$: Grid-side filter inductance, $R_{f_b}$: Resistance of grid-side filter inductor, $L_{f_c}$: Converter-side filter inductance, $R_{f_c}$: Resistance of converter-side filter inductor, $C_f$: Filter capacitance
Fig. 6. $I_C f$ feedback: Impact of feedback gain $K_{iC f}$ on the pole zero map for LCL filters with different resonance frequencies: $f_{Res} = 1.69$ kHz (left), $f_{Res} = 1.19$ kHz (middle), $f_{Res} = 0.69$ kHz (right).

Fig. 7. $U_C f$ feedback: Impact of feedback gain $K_{uC f}$ on the pole zero map for LCL filters with different resonance frequencies: $f_{Res} = 1.69$ kHz (left), $f_{Res} = 1.19$ kHz (middle), $f_{Res} = 0.69$ kHz (right).

Fig. 8. $I_C f$ feedback: Impact of feedback gain $K_{iC f}$ on the step response for LCL filters with different resonance frequencies: $f_{Res} = 1.69$ kHz (top) and $f_{Res} = 1.19$ kHz (bottom).

Fig. 9. Impact of the discretization method on the frequency characteristic of the approximated differentiators in comparison to the continuous one.

Fig. 10. $U_C f$ feedback: Impact of feedback gain $K_{uC f}$ on the step response for LCL filters with different resonance frequencies: $f_{Res} = 1.19$ kHz (top) and $f_{Res} = 0.69$ kHz (bottom).
A. Filter capacitor current feedback

Proportional $I_{Cf}$ feedback is suitable for resonance damping, that is: $K(z) = K_{ICf}$. Fig. 6 shows pole zero maps for high, medium, and low resonance frequencies. It can be seen that resonance poles can be damped into the unity circle with proper tuning of feedback gain $K_{ICf}$ only for high and medium resonance frequency. With low resonance frequency the interactions with the low frequency poles increase and resonance damping becomes impossible. Fig. 8 shows the step responses for high and medium resonance frequency, respectively. It can be seen that with proper tuning of $K_{ICf}$ resonance damping is obtained.

B. Filter capacitor voltage feedback

Basic considerations in chapter IV show that derivative feedback is necessary for resonance damping. Basically, it is similar to proportional feedback of the filter capacitor current, as $I_{Cf}(s) = s C_f U_{Cf}(s)$ holds. Theoretically, there is no difference in continuous domain but due to the discrete implementation of the differentiation there are differences even from a system theoretical point of view.

There are different possible discretization methods [17]. The frequency behavior of differentiators discretized with Forward difference, Backward difference, Tustin approximation and a continuous differerator are shown in Fig. 9. Even though Tustin gives a perfect match in the phase, the deviations in magnitude close to the Nyquist frequency are high. Root loci that are not shown in this paper indicate that the system gets unstable in any case if the Tustin approximation is used. With respect to the magnitude, forward and backward discretization yield better matches than Tustin. However, deviations in the phase occur, ±90° at the Nyquist frequency. As the forward discretization gives an implicit control algorithm backwards discretization is used here: $K(z) = K_{ICf} C_f (1 - z^{-1})/T_c$.

Fig. 7 shows pole zero maps for different resonance frequencies. It can be seen that high resonance frequency poles cannot be damped. This is due to the discrete implementation of the differerator. Fig. 9 shows that with increasing frequency the characteristic of the backward differerator changes from differerator to proportional gain, that is constant magnitude and zero phase. As proportional $U_{Cf}$-feedback is not suitable for resonance damping (see Fig. 4) no damping is obtained. For medium resonance frequency damping works well. As the interactions with low frequency poles becomes higher for low resonance frequencies stability gets worse in that case. Fig. 10 shows the step responses for medium and low resonance frequency. Proper tuning yields resonance damping. However, for low resonance frequency the resonance oscillations decay slower. Higher feedback gain $K_{UCf}$ cannot improve damping, but instead poles are pushed outside again, as can be seen in Fig. 7 (right).

Compared with $I_{Cf}$ feedback the interactions of the resonance poles with the dominant low frequency pole pair are in general higher.

Fig. 11. PI control without feedback of $I_{Cf}$ and $U_{Cf}$: measured step response of dq converter current (left) and line current (right) for medium resonance frequency.

Fig. 12. $I_{Cf}$ feedback: measured step response of dq converter current (left) and line current (right) for medium resonance frequency.

Fig. 13. $U_{Cf}$ feedback: measured step response of dq converter current (left) and line current (right) for medium resonance frequency.
VI. MEASUREMENT RESULTS

In order to validate the theoretical analysis measurements have been carried out on a laboratory test set-up with a self-built back-to-back converter feeding a 22-kW induction motor. See Table II for most important system settings. The control algorithm is implemented on a DSPACE DS 1006 board and executed twice per switching period. Unless otherwise stated, tests are carried out with motor speed of 1000 rpm. The load torque generated by a DC machine is adjusted in order to obtain a constant active power of 10 KW on the grid side. Current reference steps are applied to the reactive current component in order to test the dynamic behaviour. In steady state reactive power of 10 kVA is supplied to the grid. Harmonic compensators on the grid side as shown in [21] are not used here.

Due to parasitic damping the LCL resonance poles are naturally damped [9]. In order to clearly excite the LCL resonance also in steady state the PI gain is slightly increased by 20%. The response of the PI controlled system without feedback of any filter capacitor signal is shown in Fig. 11 and the steady state current spectra are shown in Fig. 14 (left). The currents are much distorted by the system resonance at 1.2 kHz. However, low frequency distortions due to the 5th and 7th line voltage harmonics are also visible.

The results obtained with the resonance damping approaches are shown in Figs. 12 and 14 (middle) for $I_{Cf}$ feedback and in Figs. 13 and 14 (right) for $U_{Cf}$ feedback, respectively. A fast dynamic can be seen in the step responses. There are more oscillations visible in the line side current and there is coupling between the d and q axes. The resonance is well damped, but the currents are still distorted by the low frequency line voltage harmonics. Note that harmonic compensators could reduce these distortions.

VII. CONCLUSION

Basic study of resonance damping properties show that either proportional feedback of the currents through the LCL filter capacitors or derivative feedback of the voltages across them is required. A detailed analysis with detailed discrete models and with different system settings show limitations in damping capability of these two approaches. For different ratios of resonance frequency and control frequency their behaviour is different. For high resonance frequencies only current feedback can stabilize the system. For medium resonance frequencies both approaches show good performance. For low resonance frequencies stability gets worse even though voltage feedback offers slightly better damping properties. The results in this paper are partly obtained from analyses with several typical system settings. However, they can easily be transferred to other particular settings with other parameters. For future work it can be considered to achieve stability of systems with even low LCL resonance frequencies by feedback of both, current through and voltage across the filter capacitors. Roughly speaking, the proportional voltage feedback is used for shifting the frequency into the frequency range in which the current feedback achieves resonance damping. But as the complete LCL filter state vector needs to be known anyhow, state space control approaches can be applied. In contrast to manual tuning of two damping parameters, pole placement design offers a straight-forward design procedure and the possibility of specifying desired closed-loop pole zero locations. Estimation of certain system states could reduce the sensor effort. For example the derivation of the filter capacitor voltage is a simple way of filter capacitor current estimation.

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REFERENCES


