LCL Filter

Filter Theory

The L type filter consists of an inductor only. Over the entire frequency range, L type filters have an attenuation of -20 dB/dec. In order to suppress the output current harmonics, a high value inductor is needed. A large inductance leads to a larger filter size and higher cost. Also, the high voltage drop over the large inductor worsens the system dynamics.

The LC filter is a second-order filter with an attenuation of -40 dB/dec. The LC filter design process is fairly easy. The trade-off of the design is that a higher capacitance may help reduce the cost of the inductor. However, the system may encounter inrush current and high reactive current flow into the capacitor at the fundamental frequency. Importantly, if the inverter is tied to the grid through an LC filter, the resonance frequency of the filter becomes dependent upon the grid impedance. This can create resonant frequency issues, which are a major issue. However, the LC filter is a good fit for stand-alone inverters due to its compact size and good attenuation performance.

The third-order LCL filter, is widely used with grid-connected inverters due to its high attenuation beyond resonance frequency. Compared to the LC filter, the LCL filter gives a better decoupling capability between the filter and the grid impedance as the resonant issues are already considered in the LCL filter design.

Fig. **Error! No text of specified style in document.**.1 shows a three-phase inverter with an LCL output filter. If we look at the per-phase circuit, then we get Fig. **Error! No text of specified style in document.**.2. Let's analyze this per-phase circuit to obtain an expression for the output current i_2, as we will need to control the output current to the grid. Note that we often include a series resistor in the capacitor branch for passive damping purposes, so we will assume this resistor is here for derivation of calculations (even know it is not shown in Fig. **Error! No text of specified style in document.**.2).

To do this analysis, the currents through each of the branches in the filter can be derived as (4.1-4.3) using ohm's law. Equation (4.2) can then be rearranged to solve for the node voltage V_c to obtain (4.4). If we perform nodal analysis at this node and substitute in (4.4) for V_c, then we get (4.5). Finally, simplifying this expression, we get (4.6).

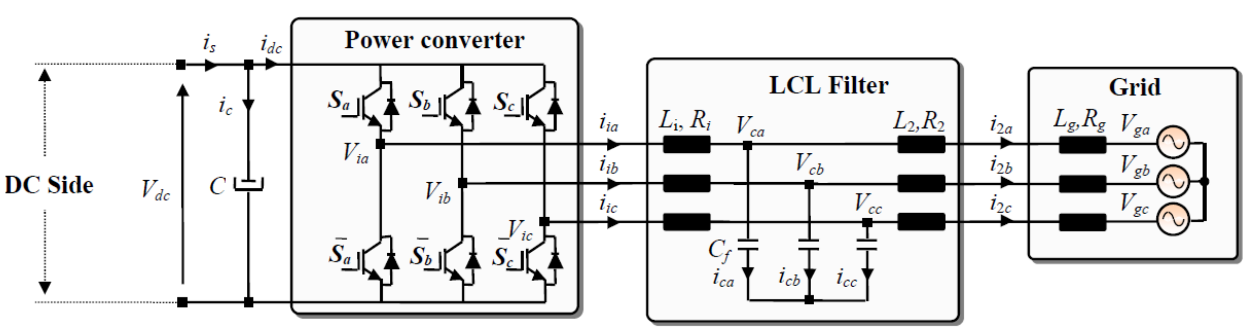

Fig. **Error! No text of specified style in document.**.1: Circuit diagram of inverter with LCL filter.

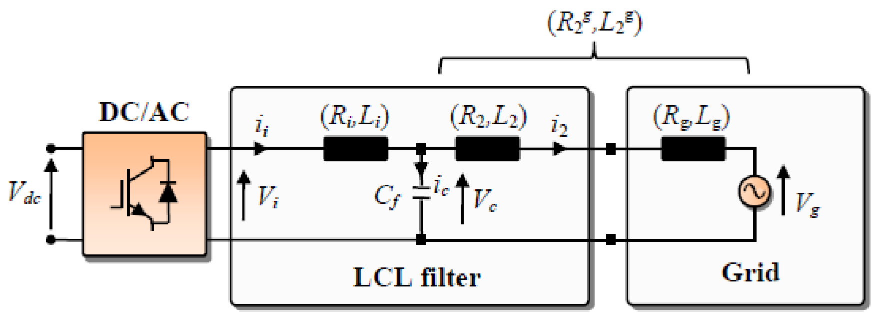

Fig. **Error! No text of specified style in document.**.2: Per-phase equivalent circuit of the inverter with LCL filter.

$$i_1 = \frac{V_1 - V_c}{sL_1 + R_1} \tag{4.1}$$

$$i_2 = \frac{V_c - V_2}{sL_2 + R_2} \tag{4.2}$$

$$i_c = \frac{V_c}{R + \frac{1}{sC}} = \frac{sCV_c}{sCR + 1} \tag{4.3}$$

$$V_C = (sL_2 + R_2)i_2 + V_2 \tag{4.4}$$

$$i_2 = i_1 - i_C = \frac{V_1 - V_c}{sL_1 + R_1} - \frac{sCV_c}{sCR + 1} = \frac{V_1 - \left((sL_2 + R_2)i_2 + V_2\right)}{sL_1} - \frac{sC\left((sL_2 + R_2)i_2 + V_2\right)}{sCR + 1} \tag{4.5}$$

$$i_2 = \frac{V_1(SCR + 1) - V_2\left(s^2CL_1 + SC(R + R_1) + 1\right)}{CL_1L_2s^3 + (CR(L_1 + L_2) + CL_1R_2 + CL_2R_1)s^2 + \left(CRR_1 + CR_1R_2 + CRR_2 + (L_1 + L_2)\right)s + (R_1 + R_2)} \tag{4.6}$$

The main objective of the LCL filter is to reduce the high-order current harmonics at the used switching frequency. Fig. Error**! No text of specified style in document.**.3 shows the equivalent per-phase circuit of the LCL filter power circuit for the *n*-harmonic waveform neglecting the effects of the resistors. To do this, we have used the theory of superposition to analyze the LCL for harmonics above the fundamental, assuming that the resistive losses R, R_1 and R_2 are zero. From Fig. **Error! No text of specified style in document.**.3, we can see that the effective grid voltage for all harmonics above the fundamental is zero because we are assuming that the grid voltage is perfectly sinusoidal.

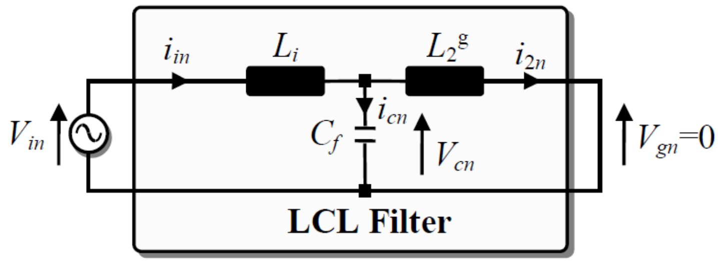

Fig. **Error! No text of specified style in document.**.3: LCL filter circuit looking at the high-frequency harmonics.

If we take (4.6) and set R, R_1 and R_2 to zero and set $V_{2,n}$ to zero, we can obtain a transfer function for the high-order harmonics (*n*-harmonics) of the output current $i_{2,n}$ over the high-order harmonics of the inverter voltage $V_{1,n}$ in (4.7).

$$H = \frac{i_{2,n}}{V_{1,n}} = \frac{1}{CL_1L_2s^3+(L_1+L_2)s} \tag{4.7}$$

The LCL filter has a resonant frequency, for the non-fundamental harmonics, where there will be very high gain as shown in Fig. **Error! No text of specified style in document.**.4. We need to make sure that this resonant frequency is not near the PWM switching harmonics or near the low frequency harmonics around 50 Hz (otherwise the filter will actually amplify these undesired harmonics). To determine resonant frequency of the transfer function, we must calculate the highest impedance. To do this, we should equate the denominator of (4.7) to zero in (4.8) and solve for ω_{res} in (4.9).

$$0 = CL_1L_2(j\omega_{\text{res}})^3 + (L_1 + L_2)(j\omega_{\text{res}}) \tag{4.8}$$

$$\omega_{\text{res}} = \sqrt{\frac{L_1+L_2}{CL_1L_2}} \tag{4.9}$$

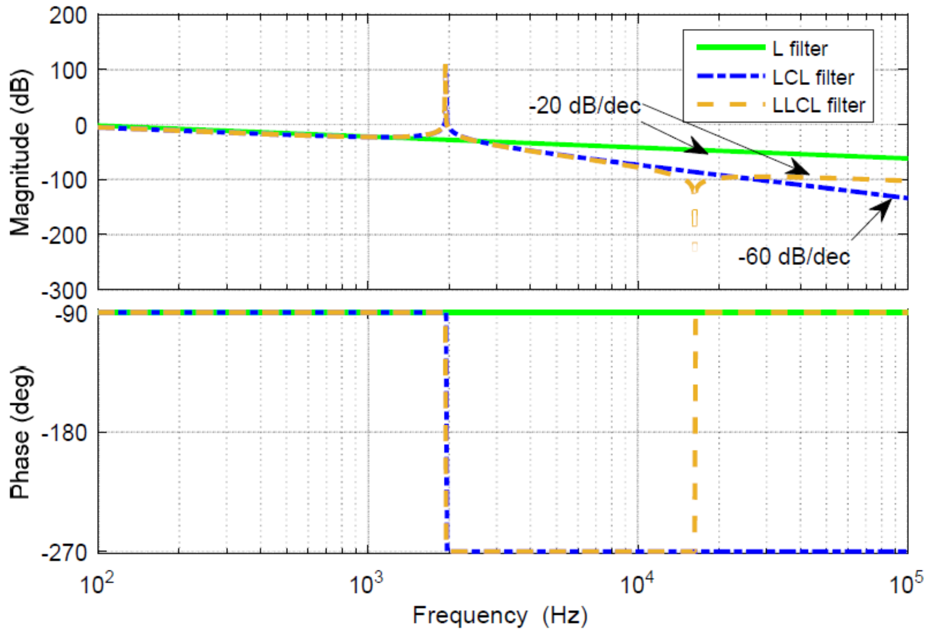

Fig. **Error! No text of specified style in document.**.4: Bode plot of different filter types.

Typically, the filter design requirements for the grid-tied mode are stricter than the design requirements for the stand-alone inverter. The filter designed for the grid-tied inverter will satisfy the stand-alone inverter operation. The inverter-side filter inductance selection is based on the allowable maximum current ripple and harmonic current attenuation. The capacitance is selected based on the reactive power absorbed at the rated conditions.

To design an LCL filter, there are some typical guidelines to follow:

- The total inductance $(L_1 + L_2)$ should be less than 10 % of the system base inductance to avoid large voltage drop across the inductors.
- The current ripple should be limited to 20 % of the rated current.
- The capacitance can neither be too large nor too small. A small value capacitance diminishes the attenuation capability of the LCL filter; however, a large value capacitance leads to a high reactive power.
- The resonance frequency of the LCL filter should always be designed within the range of (4.10) to ensure good system dynamics and avoid resonance problems.
- Also, the grid-side inductance L_2 should only be a fraction of the inverter-side inductance L_1 to improve system stability.
- The inverter current output harmonics should be limited according to IEEE 519-1992.

$10f_g < f_{\text{res}} < 0.5f_s$ where f_g is the grid frequency and f_s is the inverter sampling time (4.10)

The resonance frequency is shown in the undamped LCL filter Bode plot Fig. **Error! No text of specified style in document.**.5. The resonant poles introduced by the LCL filter may affect the system stability. To avoid this issue altogether, a passive damped LCL filter circuit is often used in the conventional PV inverter design. In this circuit, a damping resistor is either placed in parallel with the filter capacitor or in series with the filter capacitor. The damped LCL filter transfer function is derived as in (4.11), when the damping resistance is in series with the filter capacitor. The passive damped LCL filter frequency response is shown in Fig. **Error! No text of specified style in document.**.5. However, it is obvious that the damping resistor reduces the efficiency of the overall system. Thus, an active damping method is preferred.

$$i_2 = \frac{V_1(SCR+1)}{CL_1L_2s^3+CR(L_1+L_2)s^2+(L_1+L_2)s} \tag{4.11}$$

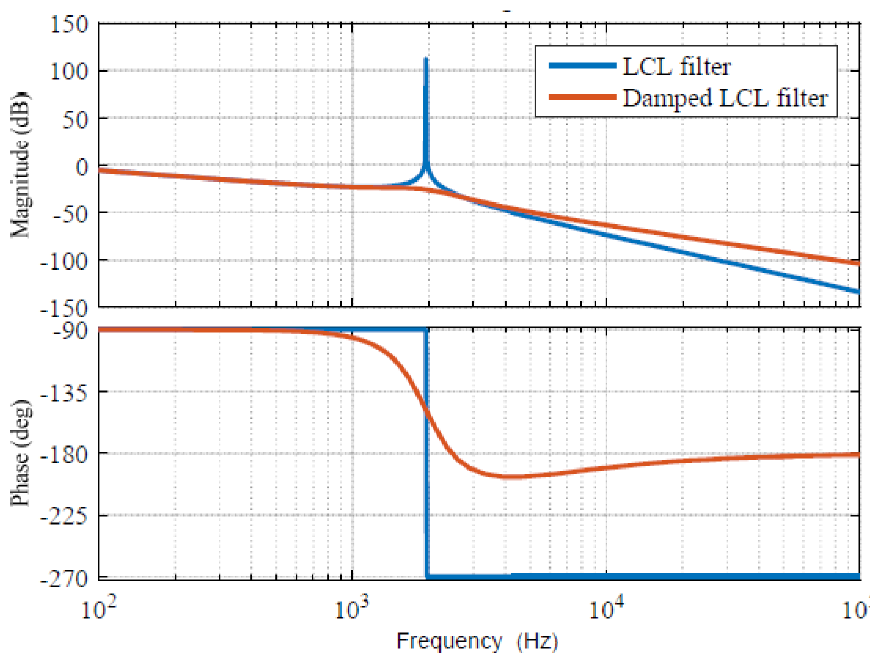

Fig. **Error! No text of specified style in document.**.5: LCL filter with passive damping resistance.

LCL filters with a resonance frequency higher than one sixth of the controller sampling frequency and below half of the controller sampling frequency, (4.12), do not require damping. However, for the LCL filters whose resonance frequency falls into the region in (4.13), require a damping technique. Many active damping techniques have been proposed and studied. Even when the damping is not required, applying resonance damping can improve the system performance. Note that active damping techniques are not covered in this document.

$$\frac{f_s}{6} < f_{\text{res}} < \frac{f_s}{2} \tag{4.12}$$

$$10f_g < f_{\text{res}} < \frac{f_s}{6} \tag{4.13}$$

Hardware Component Sizing

Firstly, we must ensure that the inverter-side inductance is large enough to filter the inverter output current ripple to a reasonable level. This ensures that the current rating of the semi-conductor switching devices (and on-state losses) are not unnecessarily high. To calculate the inverter output current ripple, we simply rearrange (2.12) to solve for $L_{1,\min}$ (4.14).

$$L_1 > \frac{v_{dc}}{12 f_{\text{sw}} \Delta i_{Lpp,\max}} \tag{4.14}$$

Next, we must ensure that the total impedance of the inductors is less than the 10% of the base impedance to avoid large voltage drop across the inductors (4.15).

$$2\pi f_g (L_1 + L_2) < 0.1 \frac{{V_{\text{rated}}}^2}{S_{\text{rated}}} \tag{4.15}$$

Next, we must ensure that the reactive power drop across the capacitor is less than 5% of the rated power to avoid large reactive power consumption across the capacitor (4.16).

$$\frac{{V_{\text{rated}}}^2}{1/2\pi f_g C} < 0.05 S_{\text{rated}} \quad ; \quad C < 0.05 \frac{S_{\text{rated}}}{2\pi f_g {V_{\text{rated}}}^2} \tag{4.16}$$

Optionally, to avoid the requirement for active or passive damping, you must ensure that the inductor and capacitor values are chosen such that the resonant frequency in between the region in (4.12) which yields (4.17).

$$\frac{f_s}{6} < \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{C L_1 L_2}} < \frac{f_s}{2} \tag{4.17}$$

Tuning PI Controllers

If we assume that the inductors and capacitors are lossless, and there are is no passive damping than the root locus of the transfer function (4.7) is Fig. **Error! No text of specified style in document.**.6. From, this diagram, there is no way that the system can achieve stability as the open-loop system never has all its poles on the LHS of the plane. Hence, we must include some resistive losses in our transfer function and in our simulation (4.24).

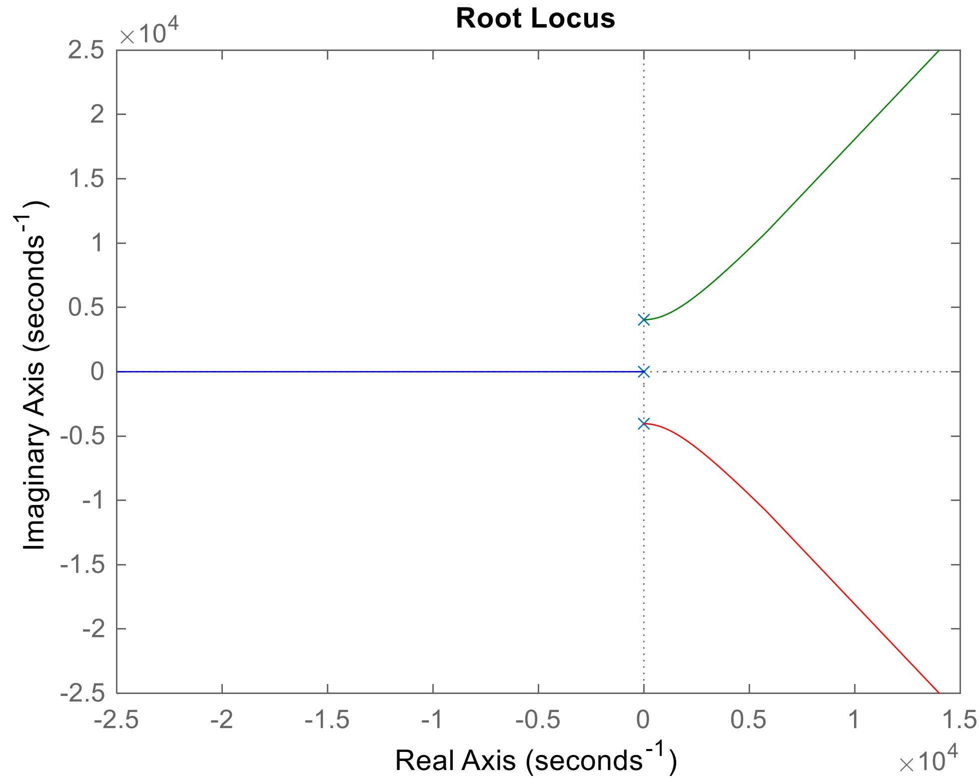

Fig. **Error! No text of specified style in document.**.6: Root locus of open-loop transfer function of output LCL current to inverter output voltage $\frac{i_{2,n}}{V_{1,n}}$ without resistive losses or damping.

$$\frac{i_{2,n}}{V_{1,n}} = \frac{(sCR+1)}{CL_1L_2s^3+(CR(L_1+L_2)+CL_1R_2+CL_2R_1)s^2+\left(CRR_1+CR_1R_2+CRR_2+(L_1+L_2)\right)s+(R_1+R_2)} \tag{4.24}$$

If the inductors have a series resistive loss of 0.1 Ω, the calculated inductances and capacitances are used and there is no passive damping, then the root locus plot in Fig. **Error! No text of specified style in document.**.7 occurs. We have all poles in the LHS of the plane, but the system will have slow dynamics and a small phase margin (small region of stability) as the poles are close to the RHS plane. Larger inductance resistances will push the poles further to the LHS and will hence increase the system dynamics and phase margin (larger stable operating range).

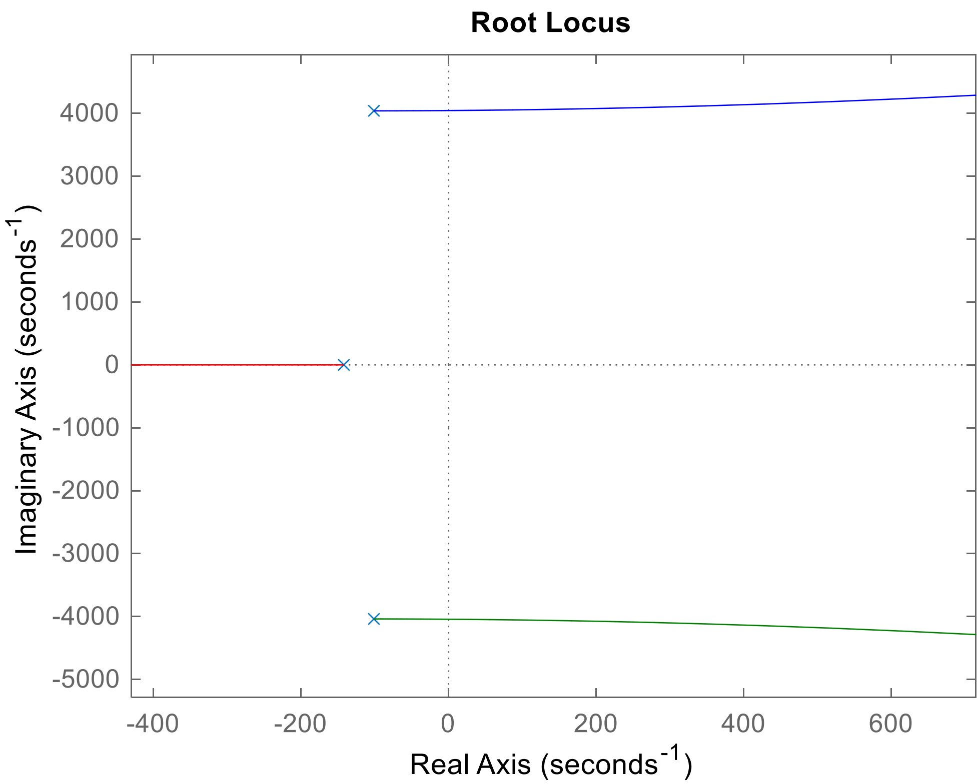

Fig. **Error! No text of specified style in document.**.7: Root locus of open-loop transfer function of output LCL current to inverter output voltage $\frac{i_{2,n}}{V_{1,n}}$ with resistive losses and no passive damping.

Hence, we may choose some passive damping if our series resistances are quite small to improve system stability and dynamics. The value of the required damping resistance for a series-connected damping resistor is (4.25). Hence, the new root locus curve with resistive losses and passive damping is shown in Fig. **Error! No text of specified style in document.**.8.

$$R_d = \frac{1}{3\omega_{\mathrm{res}}C} \tag{4.25}$$

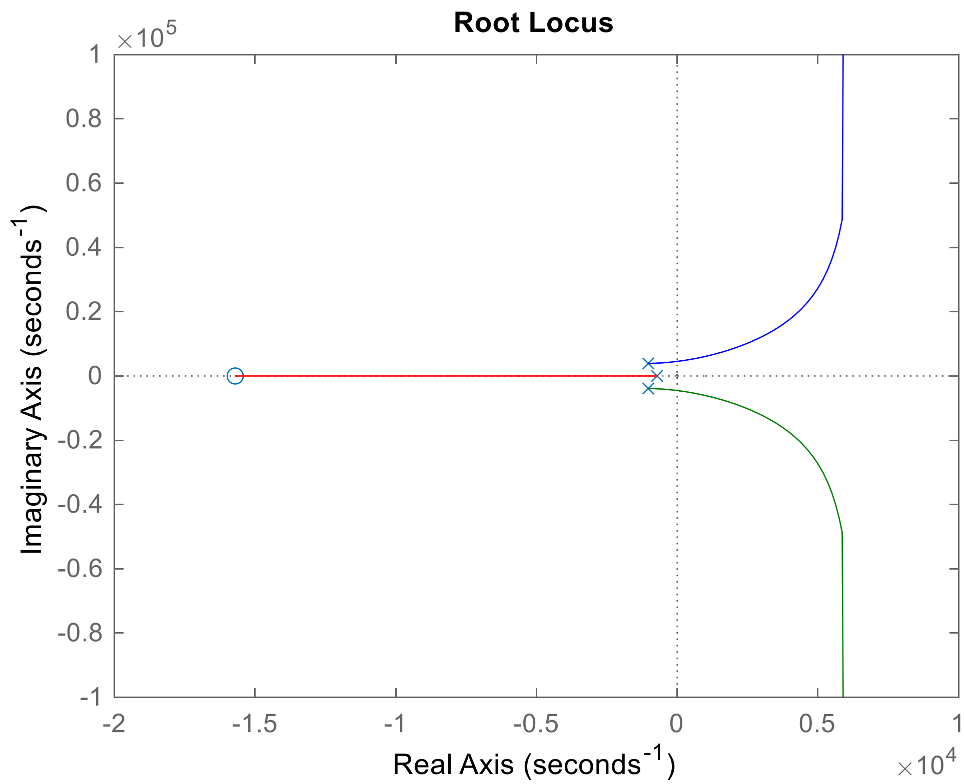

Fig. **Error! No text of specified style in document.**.8: Root locus of open-loop transfer function of output LCL current to inverter output voltage $\frac{i_{2,n}}{V_{1,n}}$ with resistive losses and series resistance passive damping.