Design of Filters for Grid-Connected Power Converters

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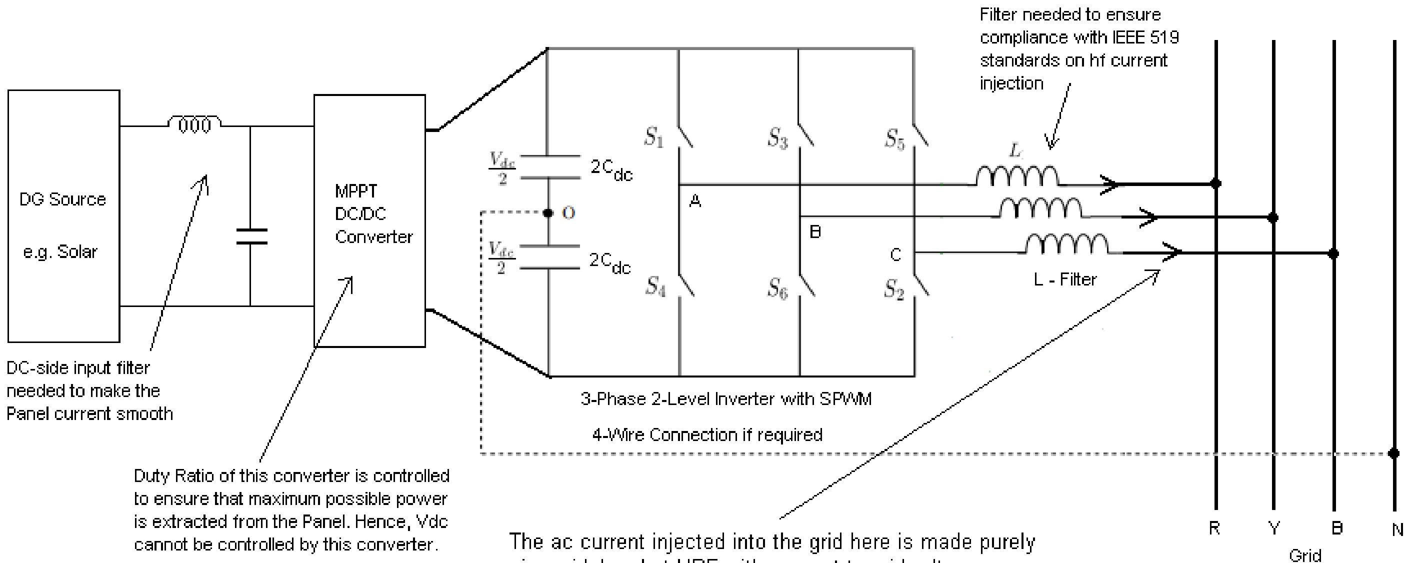
System Configuration

The System Under Study & Control Objectives



Filter needed to ensure compliance with IEEE 519 standards on hf current injection

L - Filter

DC-side input filter needed to make the Panel current smooth

3-Phase 2-Level Inverter with SPWM

4-Wire Connection if required

Duty Ratio of this converter is controlled to ensure that maximum possible power is extracted from the Panel. Hence, Vdc cannot be controlled by this converter.

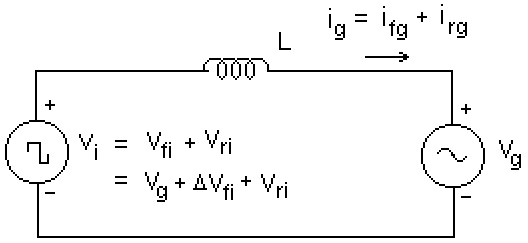
The ac current injected into the grid here is made purely sinusoidal and at UPF with respect to grid voltage.

An outer control loop which maintains the DC bus voltage constant will ensure that the amplitude of this current is such that the power injected into the grid is always equal to the power delivered by the MPPT unit to the DC side capacitor (neglecting losses).

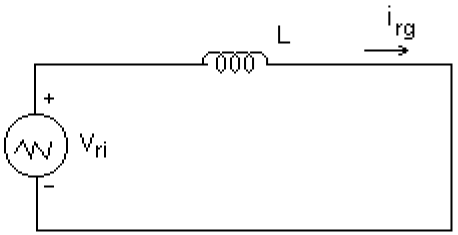
The outer DC Voltage control loop prepares the reference signal for an inner current control loop which uses the grid-injected current as a feedback signal.

Grid is assumed to be zero-impedance, pure sinusoidal, balanced three-phase source in the discussion that follow.

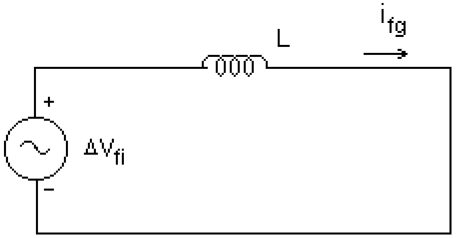
Single Phase Equivalent Circuits for Calculating Various Components of Grid-injected Current



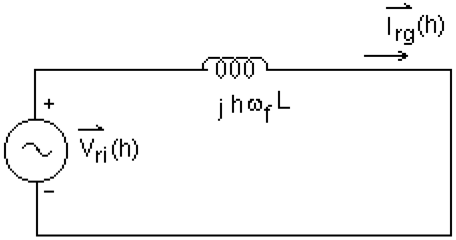
Single Phase Equivalent Circuit of Grid-connected Inverter



Single Phase Equivalent Circuit that decides ripple current in the grid-injected current



Single Phase Equivalent Circuit that decides fundamental component of grid current



Single Phase Phasor Equivalent Circuit that decides h^{th} harmonic component in ripple current

Harmonics in the Inverter Pole Voltage

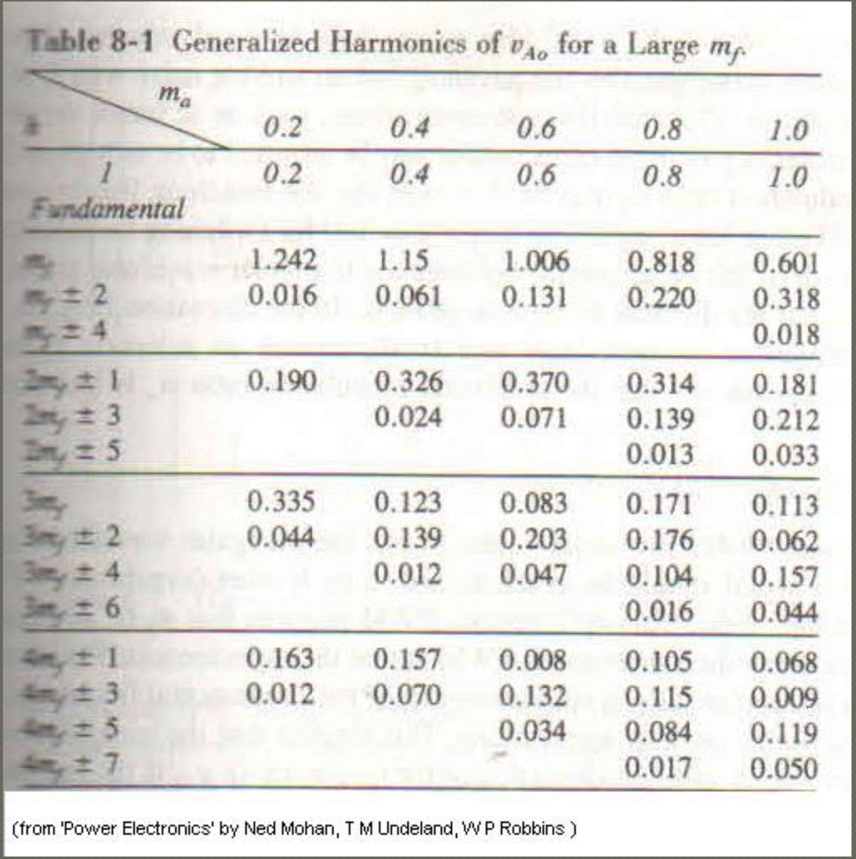


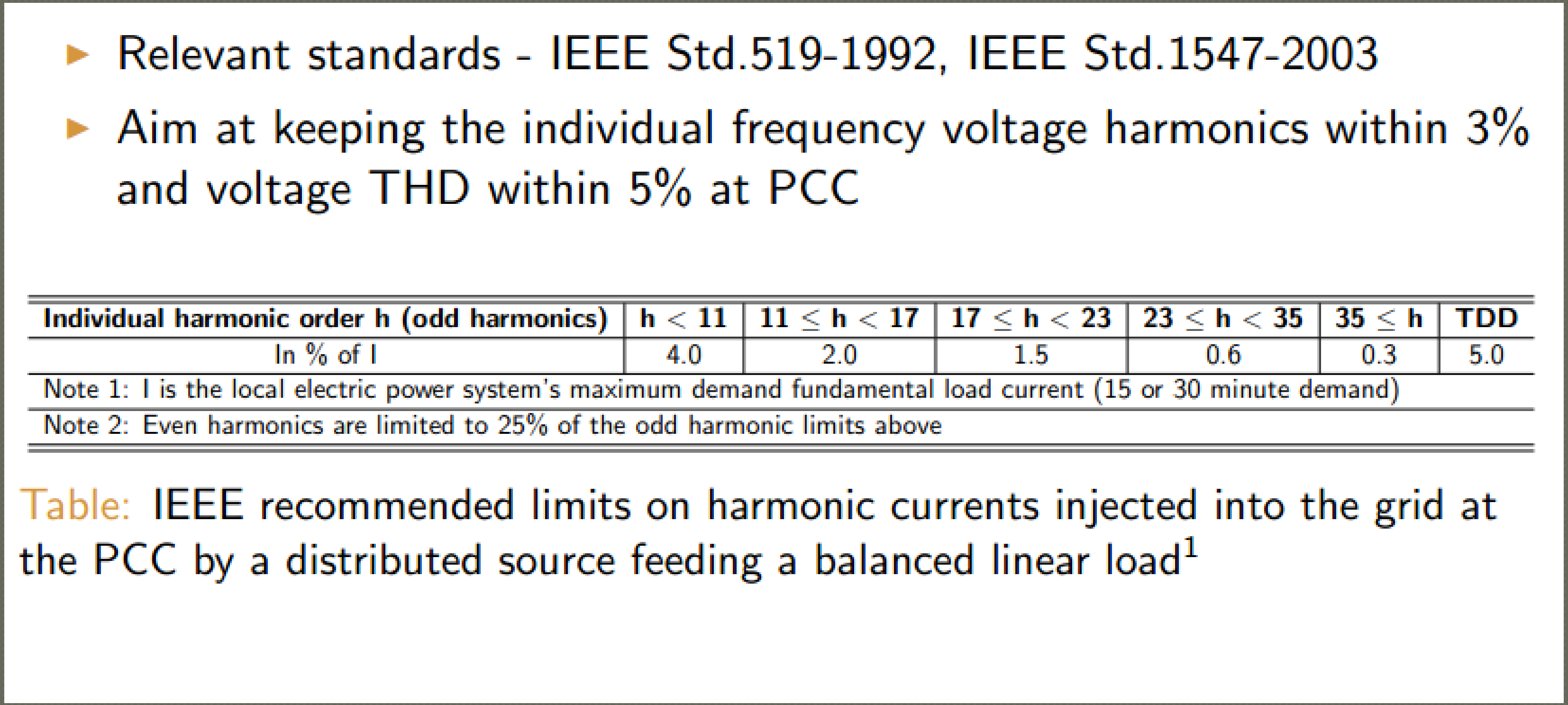
Table 8-1 Generalized Harmonics of v_{Ao} for a Large m_f.

h \ m_a	0.2	0.4	0.6	0.8	1.0
1 Fundamental	0.2	0.4	0.6	0.8	1.0
m_f	1.242	1.15	1.006	0.818	0.601
$m_f \pm 2$	0.016	0.061	0.131	0.220	0.318
$m_f \pm 4$					0.018
$2m_f \pm 1$	0.190	0.326	0.370	0.314	0.181
$2m_f \pm 3$		0.024	0.071	0.139	0.212
$2m_f \pm 5$				0.013	0.033
$3m_f$	0.335	0.123	0.083	0.171	0.113
$3m_f \pm 2$	0.044	0.139	0.203	0.176	0.062
$3m_f \pm 4$		0.012	0.047	0.104	0.157
$3m_f \pm 6$				0.016	0.044
$4m_f \pm 1$	0.163	0.157	0.008	0.105	0.068
$4m_f \pm 3$	0.012	0.070	0.132	0.115	0.009
$4m_f \pm 5$			0.034	0.084	0.119
$4m_f \pm 7$				0.017	0.050

(from 'Power Electronics' by Ned Mohan, T M Undeland, W P Robbins)

- Typical range of m_a is 0.8-0.85.
- m_f is the dominant harmonic order
- L-filter can be designed ignoring all other harmonics provided the design value is taken to be about 20% above calculated value

Allowed Harmonic Current Injection Limits



- Relevant standards - IEEE Std.519-1992, IEEE Std.1547-2003
- Aim at keeping the individual frequency voltage harmonics within 3% and voltage THD within 5% at PCC

Individual harmonic order h (odd harmonics)	**$h < 11$**	**$11 \leq h < 17$**	**$17 \leq h < 23$**	**$23 \leq h < 35$**	**$35 \leq h$**	**TDD**
In % of I	4.0	2.0	1.5	0.6	0.3	5.0
Note 1: I is the local electric power system's maximum demand fundamental load current (15 or 30 minute demand)						
Note 2: Even harmonics are limited to 25% of the odd harmonic limits above						

Table: IEEE recommended limits on harmonic currents injected into the grid at the PCC by a distributed source feeding a balanced linear load[1]

Who Does What to Satisfy IEEE 519 Requirements ?

- Typical switching frequency employed is in the range 5kHz – 15kHz
- Hence, the dominant switching harmonic content in the inverter output will be in the 100th to 300th harmonic order.
- Ripple current injection due to this harmonic content in the inverter output has to be limited to <0.3% of rated current of the inverter. The L-Filter has to do this since this frequency range will be well beyond the realisable bandwidth of the current control loop of the inverter.

Who Does What to Satisfy IEEE 519 Requirements ? (Cont'd)

- Lower order harmonics –like 3rd , 5th ,7th etc will be present in the inverter output due to blanking time, unequal switching delays in power devices, unbalanced delays in PWM generation circuitry and gate driver circuitry, unequal voltage drops in power devices etc. These harmonics may extend up to 20th in practice.
- With a switching frequency in the 5-15 kHz range, it is possible to design a current-control loop for the inverter that has a bandwidth around 1kHz. With this bandwidth, the current-control loop will reject these lower order harmonics provided the reference current given to the current-control loop is kept pure sinusoidal.

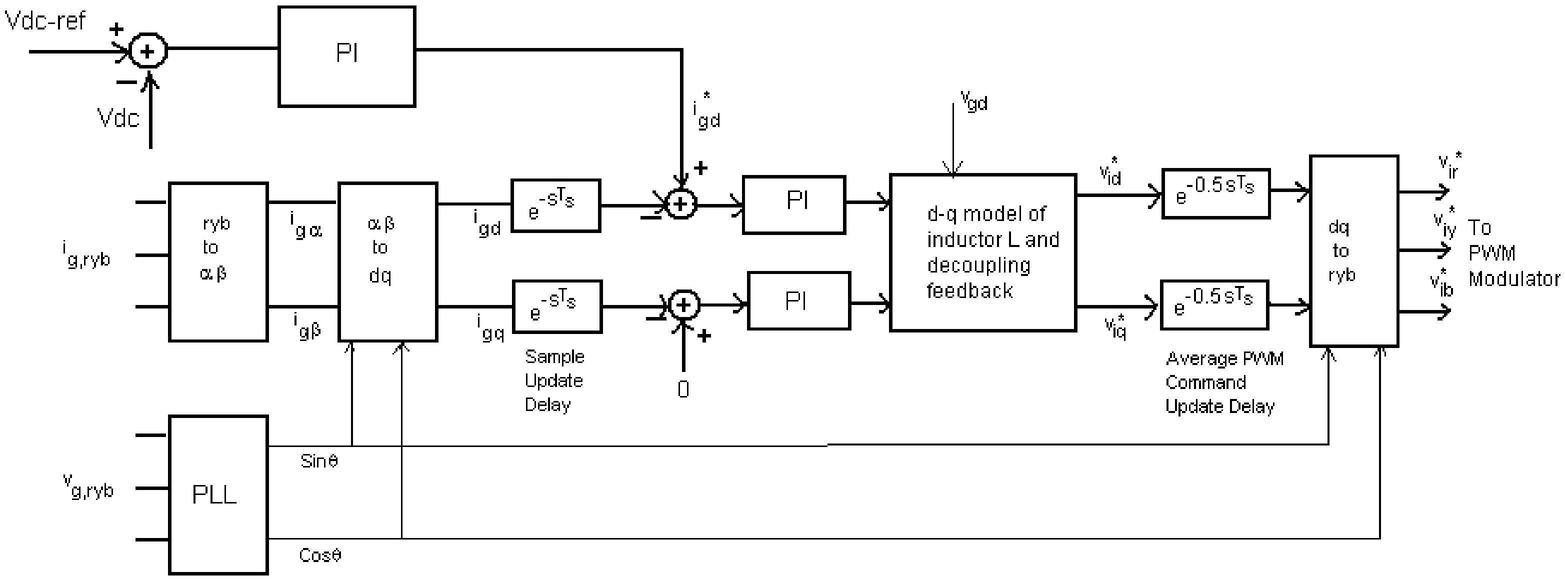
Calculating the Required L Value

- Consider a 10kVA , 400V Inverter working from 800V DC Bus. The peak value of phase voltage is 230V and the inverter will be running with m_a of 0.8. Let the switching frequency be 10kHz.
- The amplitude 10kHz component in the phase voltage will be 0.818x400 = 327.2V
- Rated current of the Inverter is 14.4A. The ripple current due to 10kHz voltage has to be limited to < 0.003x14.4x1.414 in amplitude.
- The required inductance will be > 85 mH.

And, what is wrong with L-Filter?

- The 85mH in the example puts 26.7 Ohms of reactance at 50Hz in series with the output, taking 384Vrms quadrature drop from inverter output and hence Inverter must be generating a phase voltage of 448Vrms fundamental component. That requires about 1600 V DC Bus !
- In other words, the required inductance value is simply too high and impractical.
- Conclusion : (1) IEEE 519 requirements can not be met by using L-Filter if the Inverter uses SPWM. (2) Even if the Inverter uses more advanced modulation strategies that result in lower switching harmonic levels, the L-Filter is going to be bulky, costly and lossy. Further, it will slow down the Vdc control loop response. (3) Hence, L-Filter is suitable only for inverters with low rating.

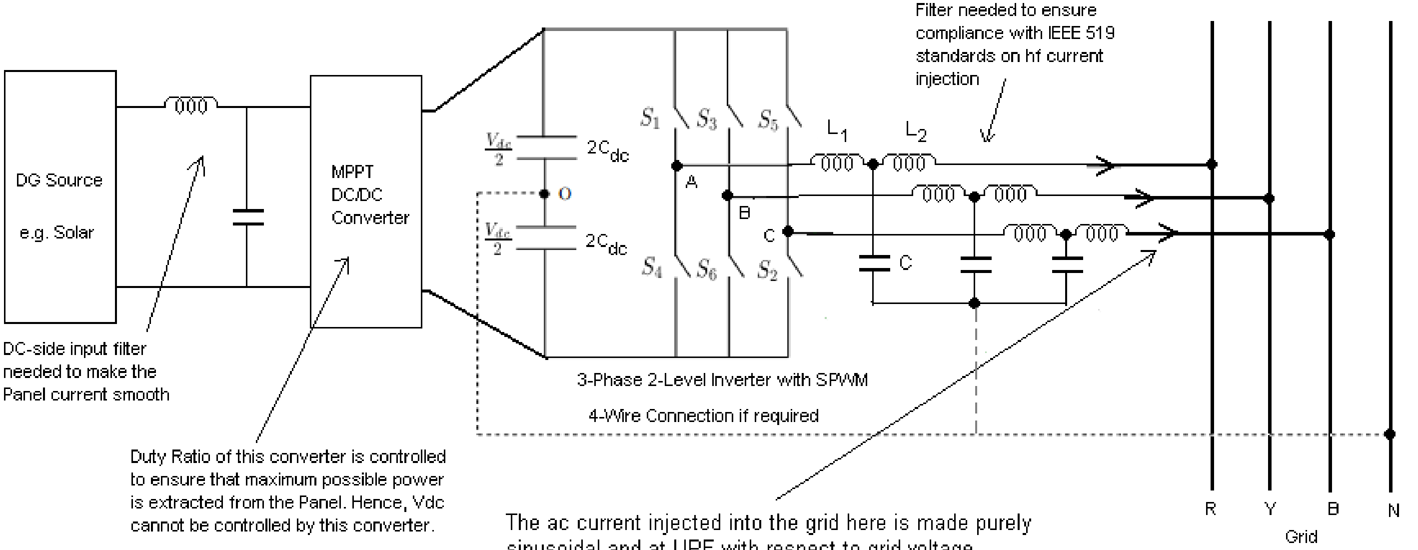
Control of Inverter with L-Filter



Phase angle contributions to Loop Gain come from the two transportation lags, PI Controller and 1/sL term in d-line and q-line

Inductor contributes 90 deg. Design of PI in d-line and q-line is done such that gain cross-over takes place at around 1 kHz with a phase margin of 45 deg. With this design,the bandwidth of closed current control loop will be above 1kHz,thereby ensuring that the current loop can reduce the content of lower harmonics (up to about 25th) in the grid-injected current to negligible levels.

Three-Phase Grid-Connected Inverter With LCL Filter



DC-side input filter needed to make the Panel current smooth

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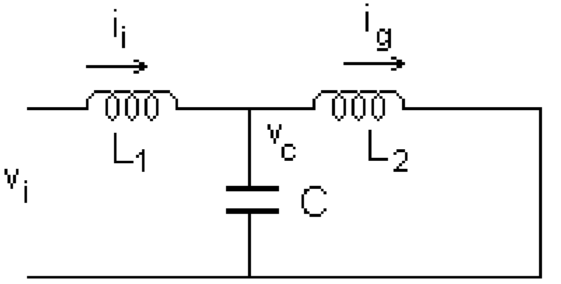
Design of Ideal LCL Filter :**Case 1 :**
Filter Resonant Frequency >> Bandwidth of Current Control Loop



Single-phase equivalent circuit for transfer function analysis

$$\frac{i_g(s)}{v_i(s)} = \frac{1}{sL(1+s^2L_pC)}$$

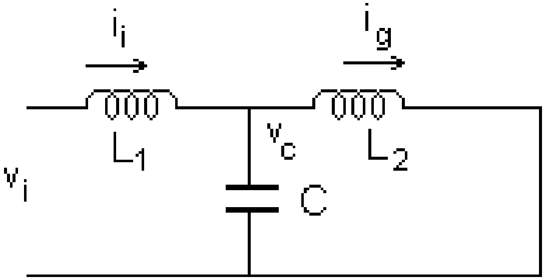
where $$L_p = \frac{L_1 \times L_2}{L_1 + L_2}$$

$$\omega_{res}^2 = \frac{1}{L_pC}$$

- Current Control Loop bandwidth has to be such that harmonics up to 25 are handled by it properly. Thus this bandwidth has to be around 1-1.5 kHz and hence Loop Gain Cross-over has to be at around 1kHz with 45 deg Phase Margin.
- But for designing the loop we need phase angle contributed by filter at the design cross-over frequency.
- Hence we decide to make the LCL ckt behave as if it is L by keeping the LCL resonant frequency above the cross-over frequency.
- This is done by selecting the LCL resonant frequency equal to geometric mean of cross-over frequency and switching frequency.

Design of Ideal LCL Filter :**Case 1** (Cont'd)

Filter Resonant Frequency >> Bandwidth of Current Control Loop



Single-phase equivalent circuit for transfer function analysis

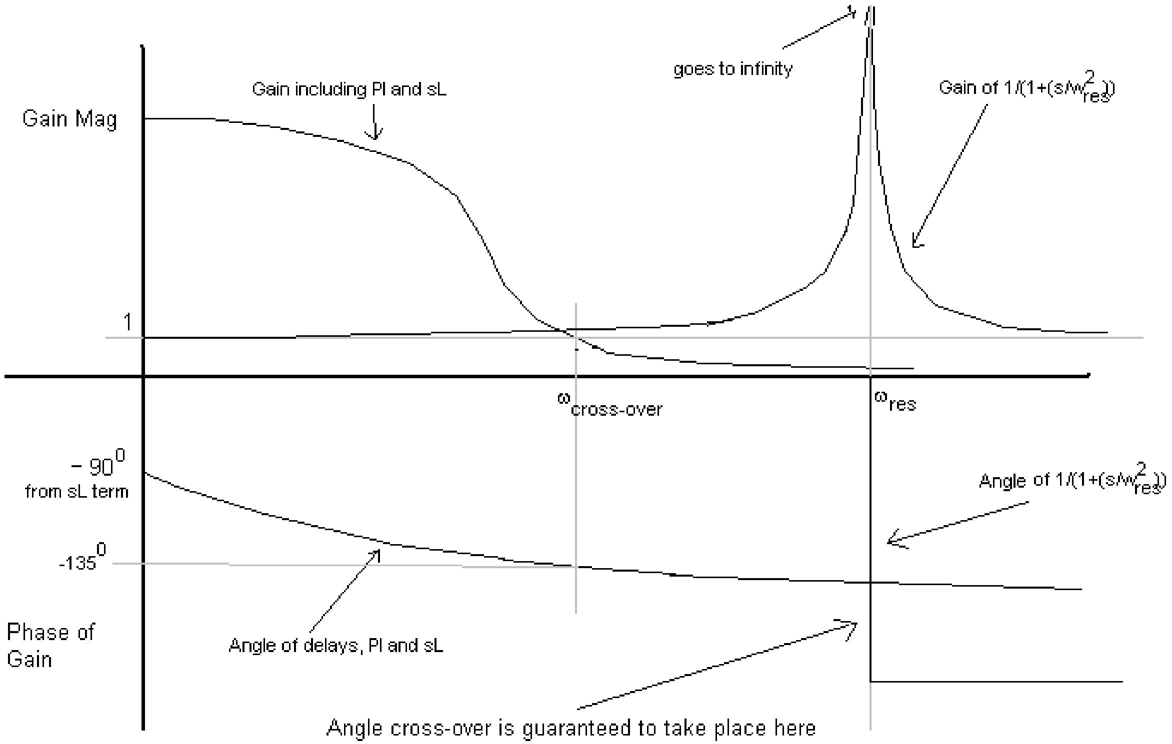
$$\frac{|i_g(j\omega_s)|}{|v_i(j\omega_s)|} = \frac{1}{\omega_s L(1 - \left(\frac{\omega_s}{\omega_{res}}\right)^2)}$$

$$C = \frac{1}{\omega_{res}^2 \times L \quad \frac{a_L}{(a_L+1)^2}}$$

- $L = L_1 + L_2$ can be found by using the known values of switching frequency voltage content in the inverter phase voltage and the allowed switching frequency current in i_g .
- Let $L_1 = a_L L_2$. Then, the value of a_L that yields minimum value of C for a fixed resonant frequency = 1. Further, the value of a_L that yields minimum value of ripple current for any frequency is also = 1.
- Hence,
- $L_1 = L_2 = L/2$, $C = 4/L(w_{res})^2$

Design of Ideal LCL Filter :Case 1 (Cont'd)

Problem : The Designed System Will be Unstable !

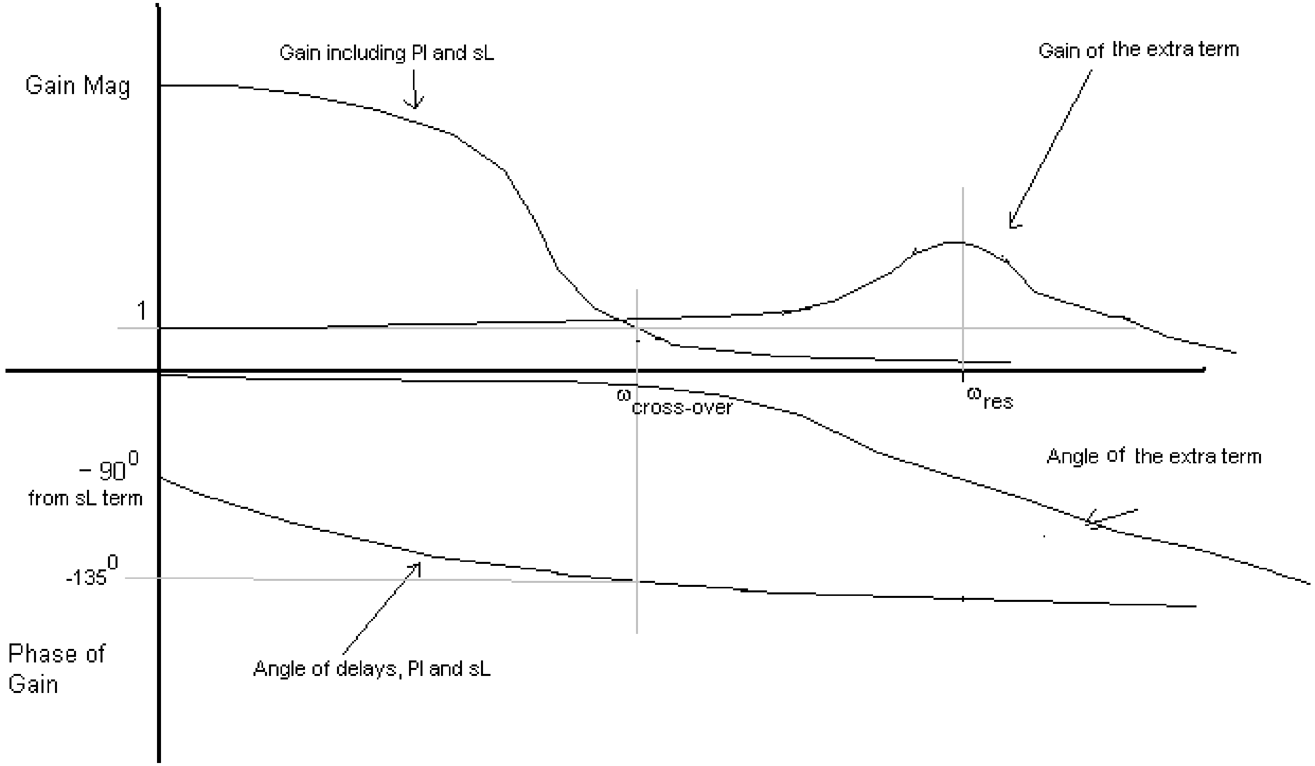


Angle cross-over is guaranteed to take place here and gain magnitude is guaranteed to be > 1. Hence instability at resonance frequency of the LCL Filter is guaranteed.

Frequency Response Plots of components of Loop Gain for Grid-connected Inverter with LCL Filter showing why the closed loop system will be unstable

Design of LCL Filter :Case 1 (Cont'd)

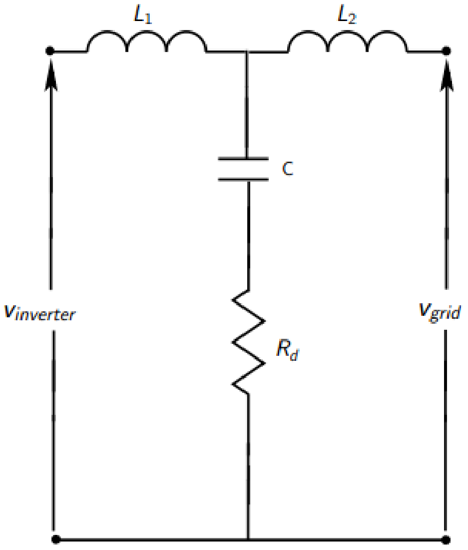
Solution : Damp the LCL Filter



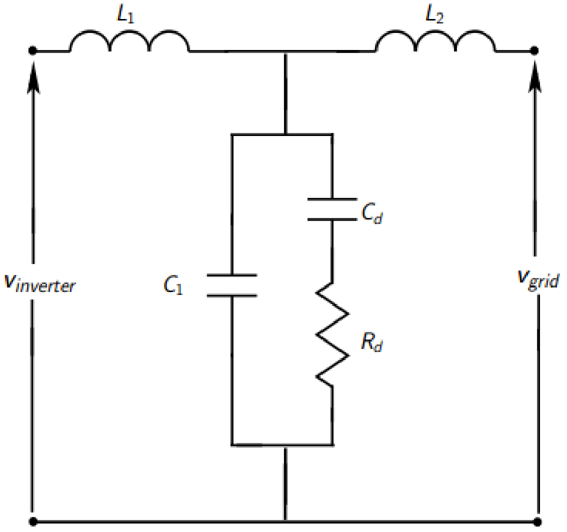
Frequency Response Plots of components of Loop Gain for Grid-connected Inverter with LCL Filter showing how damping the filter stabilises the system

Design of LCL Filter :Case 1 (Cont'd)

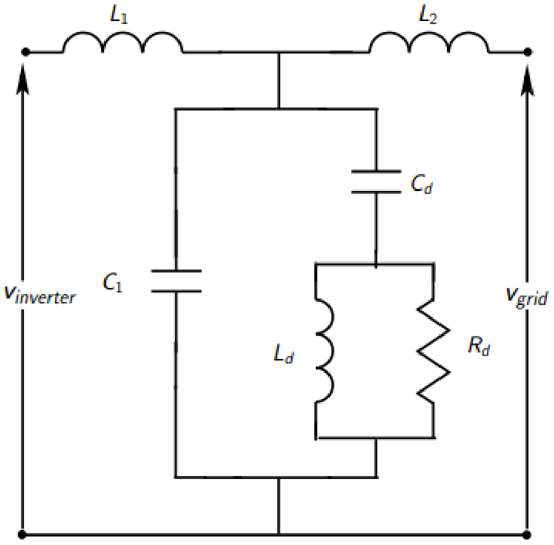
Different Damping Arrangements



R Damping



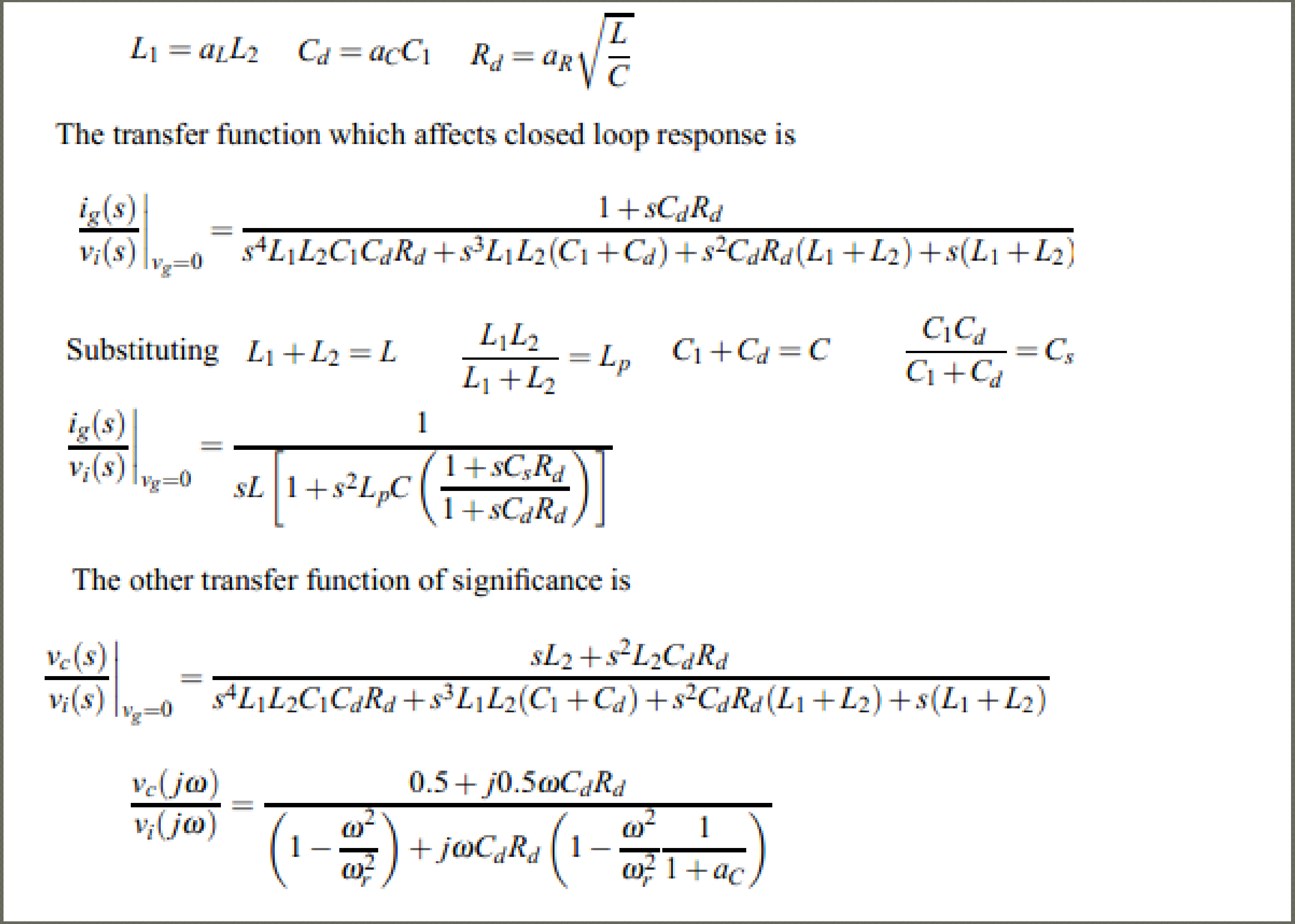
SC-R Damping



SC-RL Damping

Design of LCL Filter :**Case 1** **(Cont'd)**

With SC-R damping



$$L_1 = a_L L_2 \quad C_d = a_C C_1 \quad R_d = a_R\sqrt{\frac{L}{C}}$$

The transfer function which affects closed loop response is

$$\left.\frac{i_g(s)}{v_i(s)}\right|_{v_g=0} = \frac{1+sC_dR_d}{s^4L_1L_2C_1C_dR_d + s^3L_1L_2(C_1+C_d) + s^2C_dR_d(L_1+L_2) + s(L_1+L_2)}$$

Substituting $L_1 + L_2 = L \qquad \frac{L_1L_2}{L_1+L_2} = L_p \quad C_1 + C_d = C \qquad \frac{C_1C_d}{C_1+C_d} = C_s$

$$\left.\frac{i_g(s)}{v_i(s)}\right|_{v_g=0} = \frac{1}{sL\left[1+s^2L_pC\left(\frac{1+sC_sR_d}{1+sC_dR_d}\right)\right]}$$

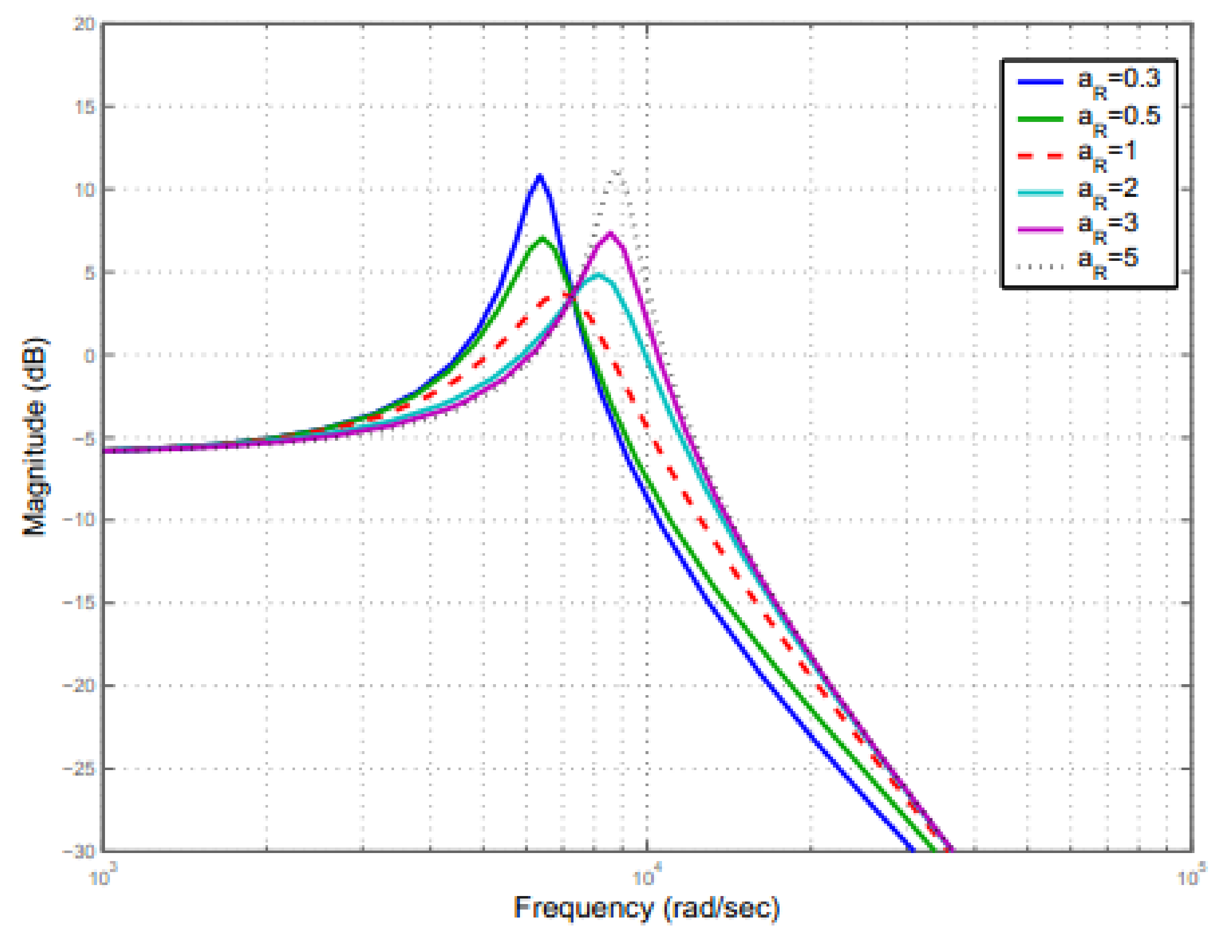
The other transfer function of significance is

$$\left.\frac{v_c(s)}{v_i(s)}\right|_{v_g=0} = \frac{sL_2 + s^2L_2C_dR_d}{s^4L_1L_2C_1C_dR_d + s^3L_1L_2(C_1+C_d) + s^2C_dR_d(L_1+L_2) + s(L_1+L_2)}$$

$$\frac{v_c(j\omega)}{v_i(j\omega)} = \frac{0.5 + j0.5\omega C_dR_d}{\left(1-\frac{\omega^2}{\omega_r^2}\right) + j\omega C_dR_d\left(1-\frac{\omega^2}{\omega_r^2}\frac{1}{1+a_C}\right)}$$

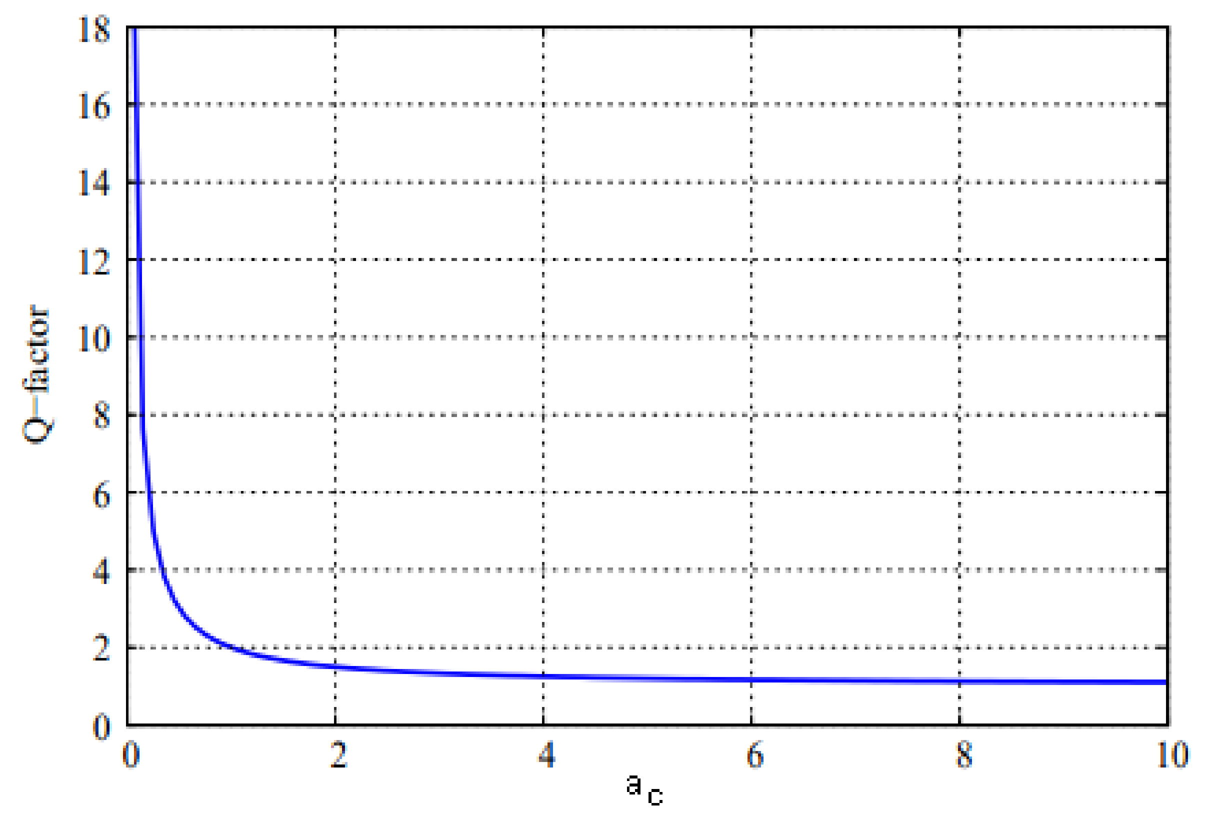
Design of LCL Filter :**Case 1** (Cont'd)

With SC-R damping: Behavior of Vc/Vi for different a_R and fixed a_C



Design of LCL Filter :**Case 1** (Cont'd)

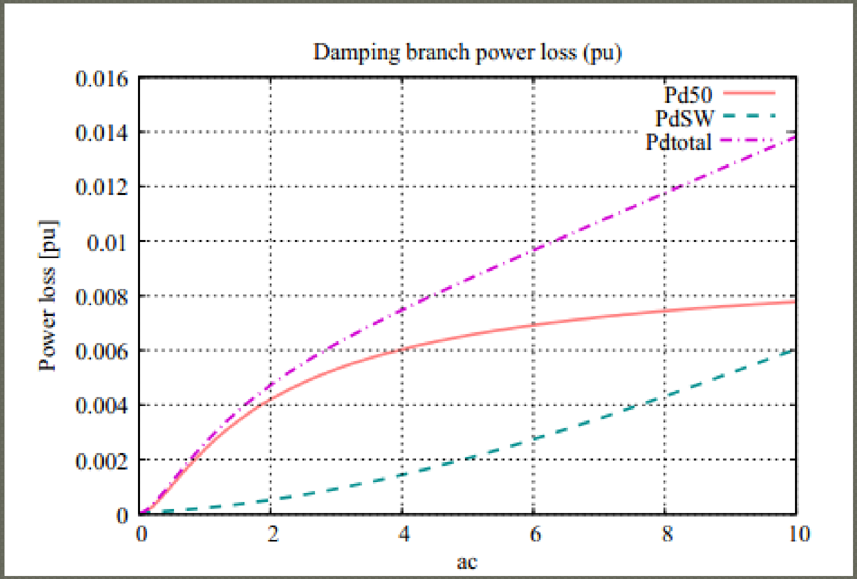
With SC-R damping: Behavior of Q Factor for different a_C and a_R =1



Design of LCL Filter :Case 1 (Cont'd)

With SC-R damping:

POWER LOSS IN DAMPING RESISTOR



DESIGN EQUATIONS FOR LCL FILTER WITH SC-R DAMPING

- Find L & C as in the case of Ideal LCL Filter
- Then $L_1 = L_2 = 0.5L$
- $C_1 = C_d = 0.5C$
- $R_d = \sqrt{(L/C)}$
- Attenuation at switching frequency has to be re-evaluated and checked

Design of LCL Filter :Case 1 (Cont'd)
With SC-R damping: Limits on L Value

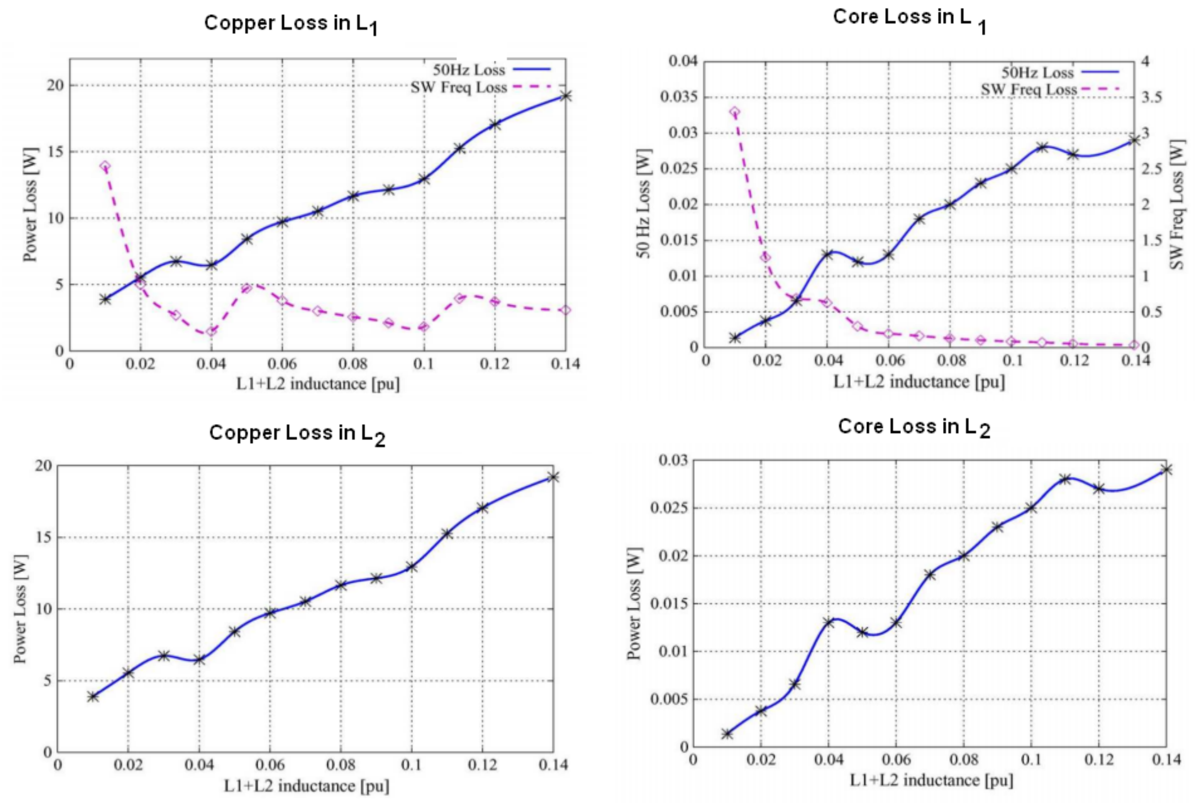
- IEEE 519 Limit for >35th harmonics sets a minimum value for L – say, L_{min}
- Power frequency voltage drop across L sets a maximum value for L – this is usually about 0.1 pu, say L_{max}
- The design procedure can - make use of any value in the (L_{min} , L_{max}) range.
- If $L > L_{min}$ is used, the hf current ripple injected will be < IEEE 519 limit.
- Copper loss in L_1 contains two components – loss due to power frequency current and loss due to switching frequency ripple current. Copper loss in L_2 is mostly due to power frequency current.
- Both components of copper loss are affected by skin effect and proximity effect in the winding; however, copper loss due to switching frequency current is very much affected by these two effects.

Design of LCL Filter :**Case 1** (Cont'd)
With SC-R damping: Limits on L Value

- Detailed expressions for ac resistance of round conductor and foil windings accounting for skin effect and proximity effect are available in literature. Further, extensive data tables and curves from which the ac resistance value can be read off directly are also available. The information needed will be the geometrical details of winding and the frequency of current.
- When $L>L_{min}$ is used, copper losses due to 50Hz current increase in both L_1 and L_2 and copper losses due to switching frequency current decrease in L_1 . Core losses due to 50Hz flux increase in both. Core loss due to switching frequency voltage across L_1 will decrease since the switching frequency flux decreases.
- Hence, as L is increased above L_{min} , it is possible that the total losses in $L_1 + L_2$ will decrease first due to decrease in copper loss and core loss in L_1 and increase after a critical value of L due to increase in 50Hz related losses – that is, total loss in $L_1 + L_2$ may exhibit a minimum at a certain value of L. That value of L is the optimum choice for L.

Design of LCL Filter :**Case 1** (Cont’d)

With SC-R damping: Total Losses in L_1 & L_2 versus L Curves



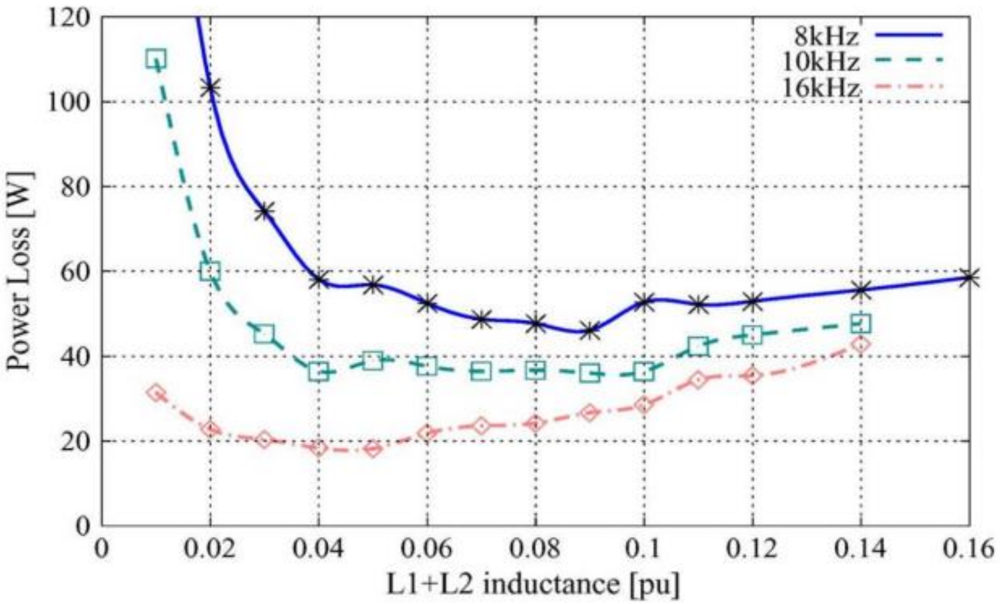
These curves are from "Optimization of Higher Order Filters for Grid-connected High Frequency Power Converters" by Dr. Vinod John and group, IISc Bangalore

Inverter Data : 10kVA, 415V, 50Hz, Switching Frequency 10kHz, LCL Resonant Frequency 1kHz
p.u Base : Inverter Rating

Design of LCL Filter :**Case 1** (Cont'd)

With SC-R damping: Total Losses in LCL Filter versus L Curve

Total Losses (including damper resistance losses) in LCL Filter versus L for different switching freqencies.



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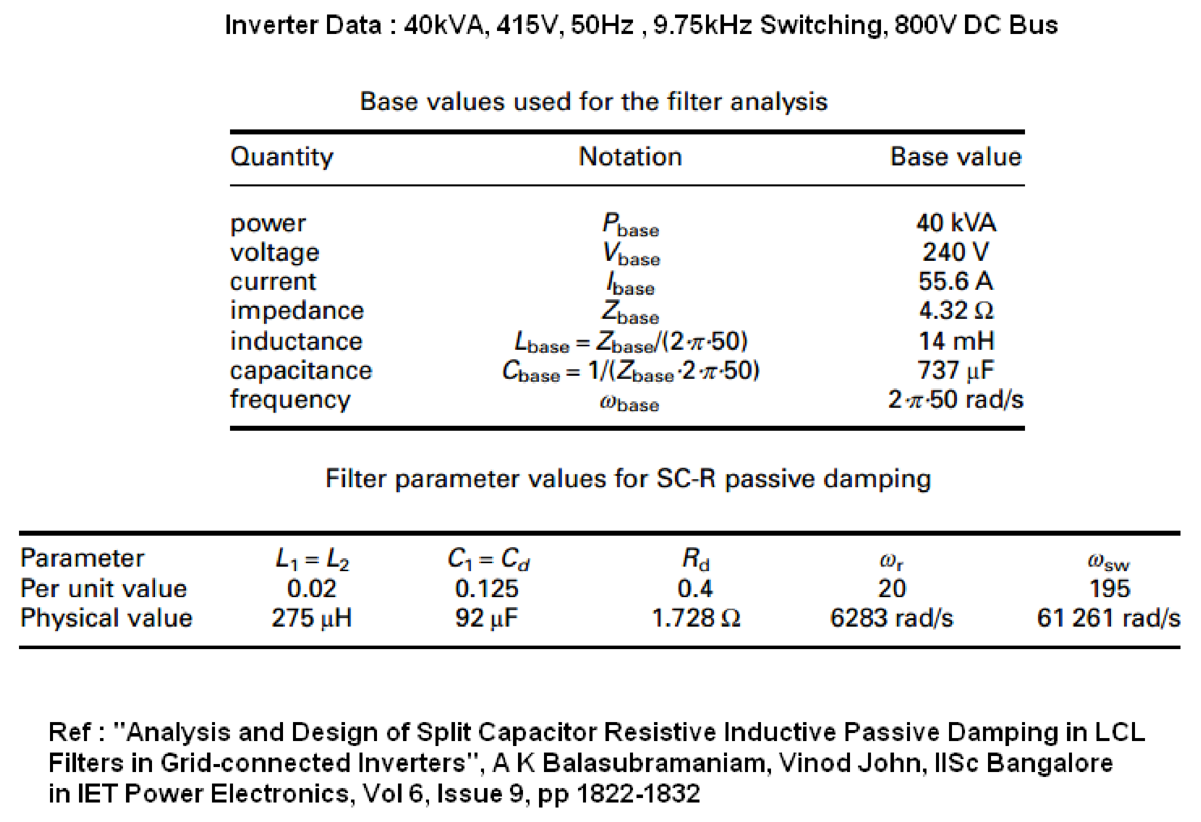
Design of LCL Filter :Case 1 (Cont'd)

With SC-R damping: An Example Design



Inverter Data : 40kVA, 415V, 50Hz , 9.75kHz Switching, 800V DC Bus

Base values used for the filter analysis

Quantity	Notation	Base value
power	P_{base}	40 kVA
voltage	V_{base}	240 V
current	I_{base}	55.6 A
impedance	Z_{base}	4.32 Ω
inductance	$L_{base} = Z_{base}/(2\cdot\pi\cdot 50)$	14 mH
capacitance	$C_{base} = 1/(Z_{base}\cdot 2\cdot\pi\cdot 50)$	737 μF
frequency	ω_{base}	$2\cdot\pi\cdot 50$ rad/s

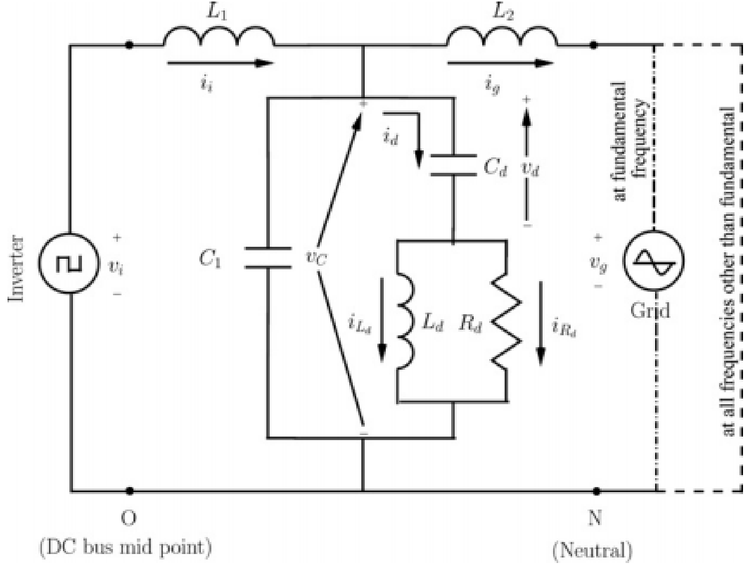
Filter parameter values for SC-R passive damping

Parameter	$L_1 = L_2$	$C_1 = C_d$	R_d	ω_r	ω_{sw}
Per unit value	0.02	0.125	0.4	20	195
Physical value	275 μH	92 μF	1.728 Ω	6283 rad/s	61 261 rad/s

Ref : "Analysis and Design of Split Capacitor Resistive Inductive Passive Damping in LCL Filters in Grid-connected Inverters", A K Balasubramaniam, Vinod John, IISc Bangalore in IET Power Electronics, Vol 6, Issue 9, pp 1822-1832

Design of LCL Filter :Case 1 (Cont'd)

With SC-RL damping:



$$\dot{X}(t) = \bar{A}X(t) + \bar{B}U(t)$$
$$Y(t) = \bar{C}X(t) + \bar{D}U(t)$$

where

$$\bar{A} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 & 0 \\ 0 & 0 & \frac{1}{L_2} & 0 & 0 \\ \frac{1}{C_1} & -\frac{1}{C_1} & -\frac{1}{C_1 R_d} & \frac{1}{C_1 R_d} & -\frac{1}{C_1} \\ 0 & 0 & \frac{1}{C_d R_d} & -\frac{1}{C_d R_d} & \frac{1}{C_d} \\ 0 & 0 & \frac{1}{L_d} & -\frac{1}{L_d} & 0 \end{bmatrix} \qquad \bar{B} = \begin{bmatrix} \frac{1}{L_1} & 0 \\ 0 & -\frac{1}{L_2} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix};$$

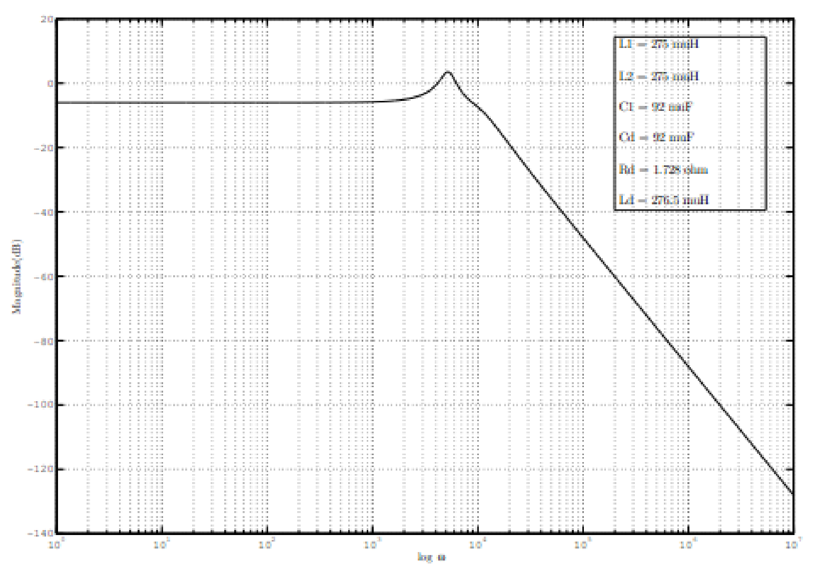
$$X = \begin{bmatrix} i_i \\ i_g \\ v_C \\ v_d \\ i_{L_d} \end{bmatrix}; \qquad U = \begin{bmatrix} v_i \\ v_g \end{bmatrix}$$

$$\frac{V_C(s)}{V_i(s)} = \frac{R_d\, L_2\, s + L_2\, L_d\, s^2 + R_d\, C_d\, L_2\, L_d\, s^3}{R_d(L_1 + L_2)s + (L_1 + L_2)L_d s^2 + R_d[L_1 L_2(C_1 + C_d) + L_d C_d(L_1 + L_2)]s^3 + L_1 L_2(C_1 + C_d)L_d s^4 + R_d L_1 L_2 C_1 C_d L_d s^5}$$

Design of LCL Filter :Case 1 (Cont'd)

With SC-RL damping:

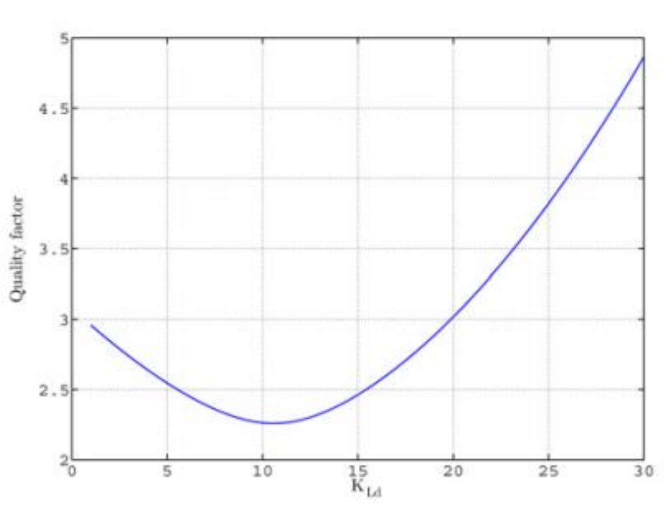
- SC-R design is done first. Then L_d has to be decided. A factor, K_{Ld} is defined as = R_d / w_f L_d where w_f is the fundamental frequency.
- The transfer function V_c (s)/V_i (s) is a low pass function. The ratio of maximum frequency response gain to the DC gain is the Quality Factor of the Filter.
- Frequency response is plotted for various values of K_{Ld} in the 0 to 30 range and Q Factor is noted in each case.

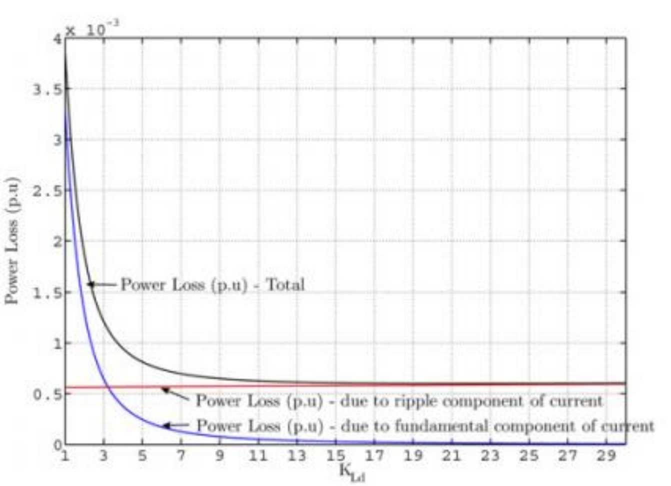


Design of LCL Filter :Case 1 (Cont'd)

With SC-RL damping:

- For each value of K_{Ld} , the 50Hz power loss in R_d is calculated by solving the Filter Circuit for 50Hz and the switching harmonic current related power loss is obtained by state-space simulation of the entire system. Thus, the total loss in R_d is calculated.
- Plots of Q Vs K_{Ld} show that Q is a minimum when K_{Ld} is around 10 and that the total loss in R_d is near minimum with K_{Ld} around 10.
- Hence K_{Ld} = 10 is accepted as the design value for the example.





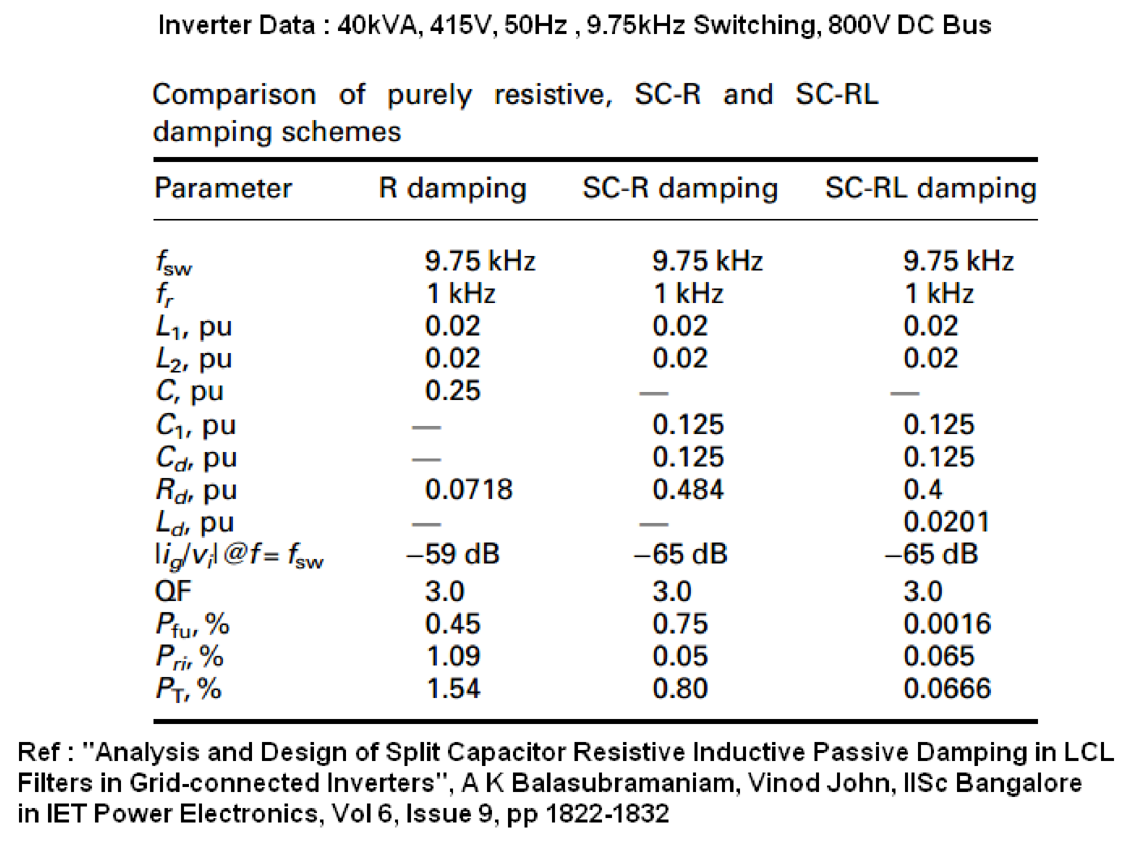
Design of LCL Filter :Case 1 (Cont'd)

With SC-RL damping:

- Detailed numerical simulation shows that the optimum value of $K_{Ld} = 0.5\omega_{res} / \omega_f$ (which is around 10 in the example) and that the optimum value is independent of switching frequency.
- With $L_1 = L_2$, $C_1 = C_d$, $R_d = \sqrt{L/C}$, the LCL Filter with SC-R damping will have two real poles and two complex poles. The complex poles are at $(-0.225 \pm j\ 1.113)\ \omega_{res}$ indicating that the design results in a fixed damping factor independent of the choice of resonance frequency
- With $L_1 = L_2$, $C_1 = C_d$, $R_d = \sqrt{L/C}$, $L_d = 2R_d / \omega_{res}$ the LCL Filter with SC-RL damping will have one real pole and two repeated complex conjugate pole pairs. The complex poles are at $(-0.5 \pm j\ 0.866)\ \omega_{res}$ indicating that the design results in a fixed damping factor independent of the choice of resonance frequency

Design of LCL Filter :Case 1 (Cont'd)

Comparison of R, SC-R and SC-RL Damping:



Inverter Data : 40kVA, 415V, 50Hz , 9.75kHz Switching, 800V DC Bus

Comparison of purely resistive, SC-R and SC-RL damping schemes

Parameter	R damping	SC-R damping	SC-RL damping
f_{sw}	9.75 kHz	9.75 kHz	9.75 kHz
f_r	1 kHz	1 kHz	1 kHz
L_1, pu	0.02	0.02	0.02
L_2, pu	0.02	0.02	0.02
C, pu	0.25	—	—
C_1, pu	—	0.125	0.125
C_d, pu	—	0.125	0.125
R_d, pu	0.0718	0.484	0.4
L_d, pu	—	—	0.0201
$\lvert i_g/v_i \rvert$ @$f = f_{sw}$	–59 dB	–65 dB	–65 dB
QF	3.0	3.0	3.0
P_{fu}, %	0.45	0.75	0.0016
P_{ri}, %	1.09	0.05	0.065
P_T, %	1.54	0.80	0.0666

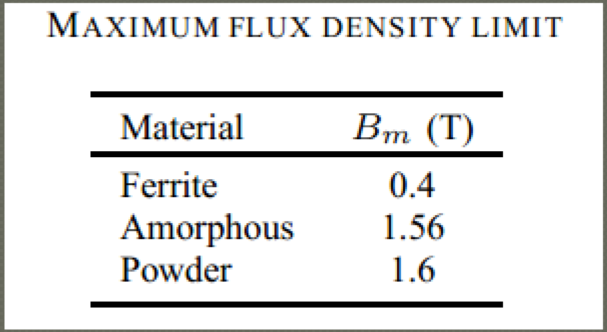
Ref : "Analysis and Design of Split Capacitor Resistive Inductive Passive Damping in LCL Filters in Grid-connected Inverters", A K Balasubramaniam, Vinod John, IISc Bangalore in IET Power Electronics, Vol 6, Issue 9, pp 1822-1832

Design of LCL Filter :Case 1 (Cont'd)

Design of Inductors:

(Ref: "Integrated approach to filter design for grid-connected power converters", MS Thesis by Parikshith B.C, 2009, IISC Bangalore)

$$A_p = \frac{V_f I_f}{k_f k_u f B_m J_m}$$



MAXIMUM FLUX DENSITY LIMIT

Material	B_m (T)
Ferrite	0.4
Amorphous	1.56
Powder	1.6

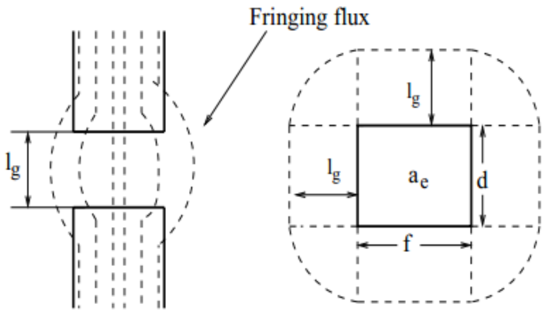
$$L = \frac{N^2}{\Re_t}$$

$$B_m = \frac{N\, I_p}{A_e\, \Re_t}$$

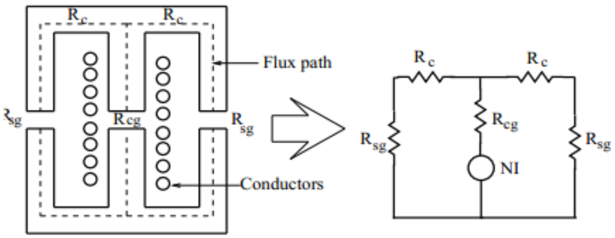
$$L = f(N, l_g)$$

$$B_m = g(N, l_g)$$

$$\Re_g = \frac{l_g}{\mu_0[a_e + 2(f+d)l_g + \pi l_g^2]}$$



Effective area considered for calculation



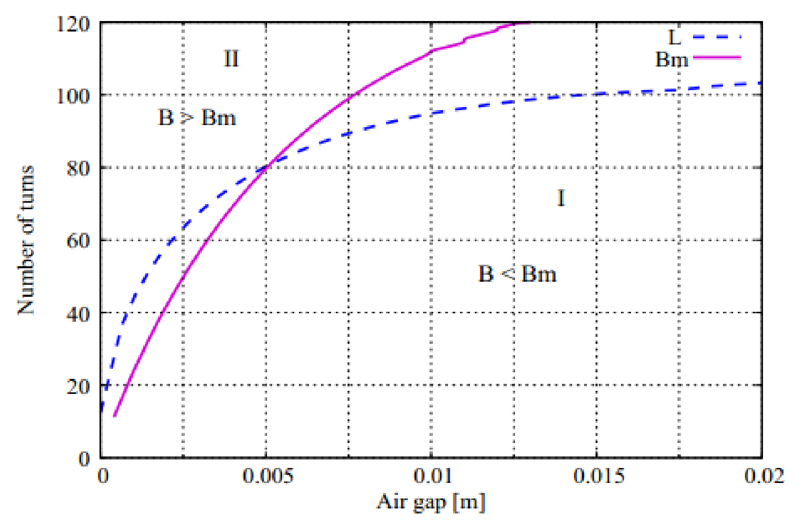
Magnetic circuit representation of EE core inductor

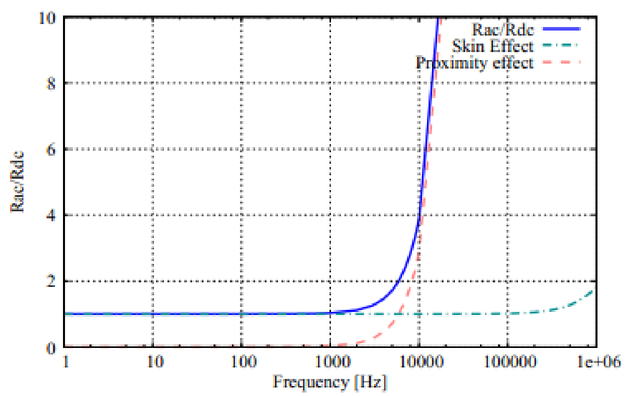
$$\Re_t = \Re_{cg} + \frac{\Re_{sg}}{2} + \frac{\Re_c}{2}$$

Design of LCL Filter :Case 1 (Cont'd)

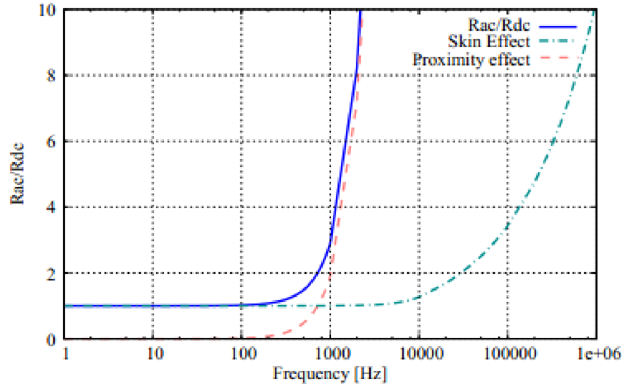
Design of Inductors (Cont'd):

(Ref: "Integrated approach to filter design for grid-connected power converters", MS Thesis by Parikshith B.C, 2009, IISC Bangalore)





R_{ac}/R_{dc} for foil winding



R_{ac}/R_{dc} for round wire winding

Design of Ideal LCL Filter :**Case 2 :**

Filter Resonant Frequency < Bandwidth of Current Control Loop

- In this case the LCL filter can be damped passively or actively.
- The final bandwidth that is required for current-control loop is around 1 to 1.5 kHz and hence the cross-over frequency has to be around 1kHz.
- Hence choose filter resonance frequency in the range 800Hz to 1kHz

References

- “Optimisation of Higher Order Filters for Grid-connected High Frequency Power Converters”, Dr. Vinod John et.al, IISc Bangalore, 2009, Report of NaMPET funded research project
- “Integrated approach to filter design for grid-connected power converters”, MS Thesis report by Parihshith B C, IISc Bangalore, 2009