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Design of *LLCL*-filter for Grid-Connected Converter to Improve Stability and Robustness

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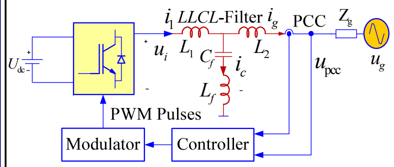
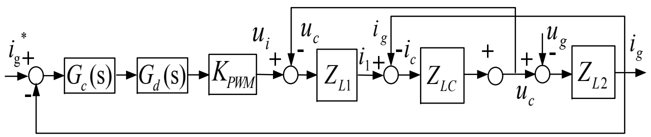
System Description

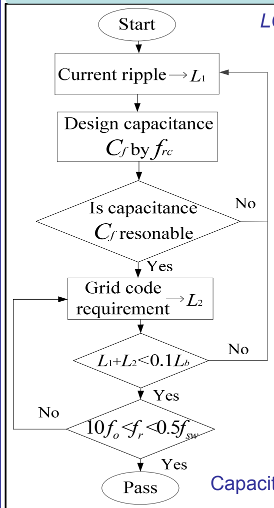


Symbol	Definition	Value
U_{dc}	DC link voltage	650 V
U_g	Grid phase voltage	220 V
f_o	Grid frequency	50 Hz
$T_s = 1/f_s$	Sampling period	100 μs
$f_{sw} = f_s$	Switching frequency	10 kHz



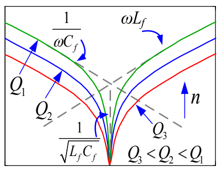
$$G_d(s) = e^{-\lambda s T_s} \qquad G_c(s) = K_p + \sum_{h=1,5,7} \frac{K_{ih} s}{s^2 + (\omega_0 h)^2}$$

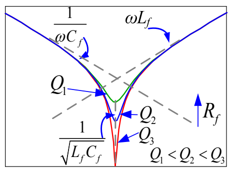
Parameter Design Procedure



Flow chart

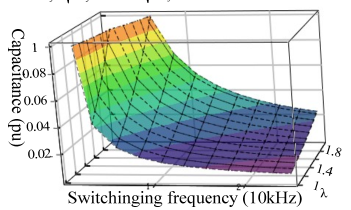
LC trap impedance with *n* LC trap impedance with R_f



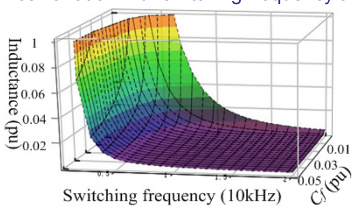


$$Q = \frac{1}{R_f}\sqrt{\frac{L_f}{C_f}} \qquad n = \sqrt{\frac{L_f}{C_f}}$$

$10 \le Q \le 50$



Capacitance variation with switching frequency and delay λ



Total inductance variation with capacitance and switching frequency

Abstract

This paper proposes a new design method for *LLCL*-filter from the point of stability and robustness of the overall system, when the grid-side current control is used. Based on this design method, the system can be stable without damping and also robust against the grid parameters variation. The influence of delay and parameter variations are analyzed in details. Last, a the method has been applied to the development of an *LLCL*-filter for testing in the laboratory with a 5-kW, 380-V, 50-Hz grid converter. The method can also be applied to the lower order *LCL*-filter with only a slight modification needed.

Stability and Robustness

Concept of Passivity

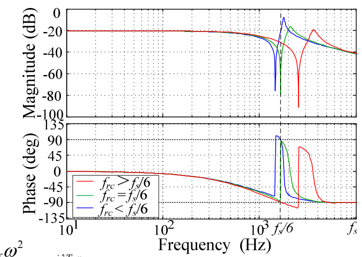
$G(s)$ has no right-half-plane (RHP) poles

$$\{G(j\omega)\} \ge 0 \Leftrightarrow \arg\{G(j\omega)\} \in [-90^\circ, 90^\circ], \forall \omega > 0.$$

$$f_{rc} = \frac{1}{2\pi\sqrt{(L_1+L_f)C_f}}$$

$$f_{sw} = 1/\left(2\pi\sqrt{L_f C_f}\right)$$

$$f_{rd} = \frac{f_s}{4\lambda}$$



$$G_{2T} = \frac{G_2}{T} = \frac{1-(L_1+L_f)C_f\omega^2}{K_{PWM}K_p(1-C_f L_f\omega^2)} e^{j\lambda T_s \omega}$$
$$= \frac{1-(L_1+L_f)C_f\omega^2}{K_{PWM}K_p(1-C_f L_f\omega^2)}[\cos(\lambda T_s\omega) + j\sin(\lambda T_s\omega)]$$

$$Re\{G_{2T}\} = \frac{1-(\omega/(2\pi f_{rc}))^2}{K_{PWM}K_p(1-(\omega/(2\pi f_r))^2)} cos(\frac{\pi}{2} \times \frac{\omega}{(2\pi f_{rd})})$$

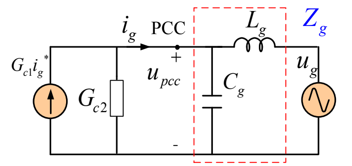
By setting $f_{rc} < f_{rd}$, $Re\{G_{2T}\}$ will be negative in the range of $f_{rc} < \omega/(2\pi) < f_{rd}$.
By setting $f_{rd} < f_{rc}$, $Re\{G_{2T}\}$ will be negative in the range of $f_{rd} < \omega/(2\pi) < f_{rc}$.
By setting $f_{rc} = f_{rd}$, $Re\{G_{2T}\}$ will always be positive.

Criterion for Stability and Robustness without Damping:

Try to make $f_{rc} = f_{rd} = f_s/6$

$f_{rd} = f_s/6 \le f_{rc} < f_r$

Norton equivalent model

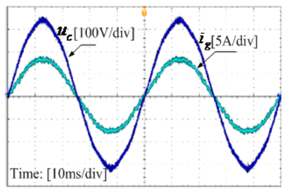


$$T = K_{PWM}G_c G_d G_1 \qquad G_1 = \left.\frac{i_g}{u_i}\right|_{u_{pcc}=0} = \frac{Z_{CL}}{Z_{L1}Z_{L2}+Z_{L1}Z_{CL}+Z_{L2}Z_{CL}}$$

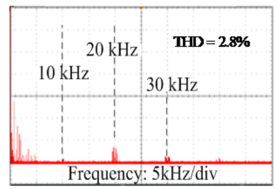
$$G_{c1} = \frac{T}{1+T}$$

$$G_{c2} = \frac{G_2}{1+T} = 1/(\frac{1}{G_2}+\frac{T}{G_2}) \qquad G_2 = \left.\frac{i_g}{u_{pcc}}\right|_{u_i=0} = \frac{Z_{L1}+Z_{CL}}{Z_{L1}Z_{L2}+Z_{L1}Z_{CL}+Z_{L2}Z_{CL}}$$

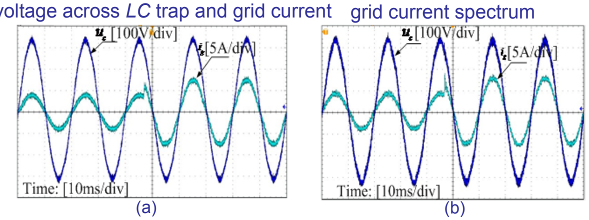
Experimental Results



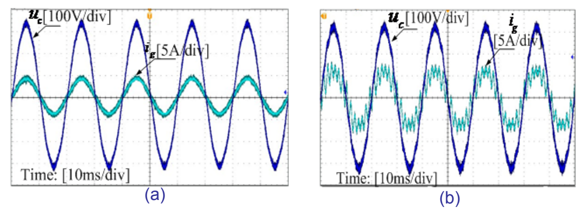
voltage across *LC* trap and grid current



grid current spectrum



voltage across *LC* trap and grid current (a) Lg = 0 mH (b) Lg = 4.8mH



voltage across *LC* trap and grid current with the same L_g=2mH and C_g=6.7 μF, but different C_f ((a) C_f=4 μF and (b) C_f=8 μF).