Analytical Expression for DC Link Capacitor Current in a Cascaded H-Bridge Multi-Level Active Front-End Converter

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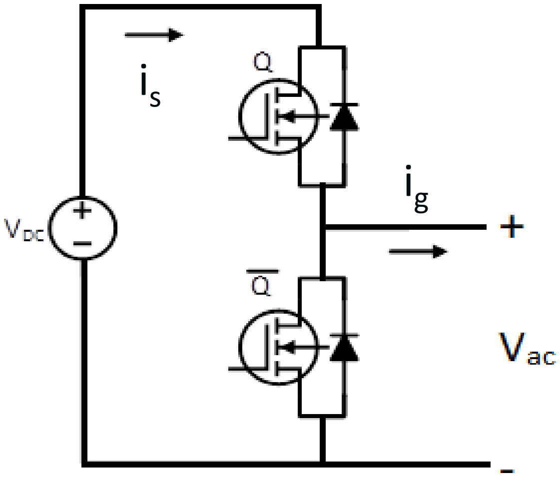
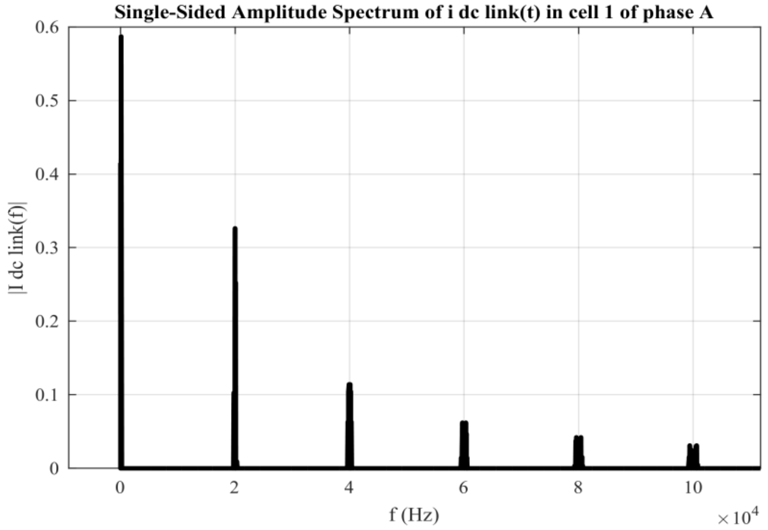
PWM driven DC Link Current– introduction

- DC link current is a time-segmented version of AC side current – harmonics caused by switching



PWM-driven half bridge

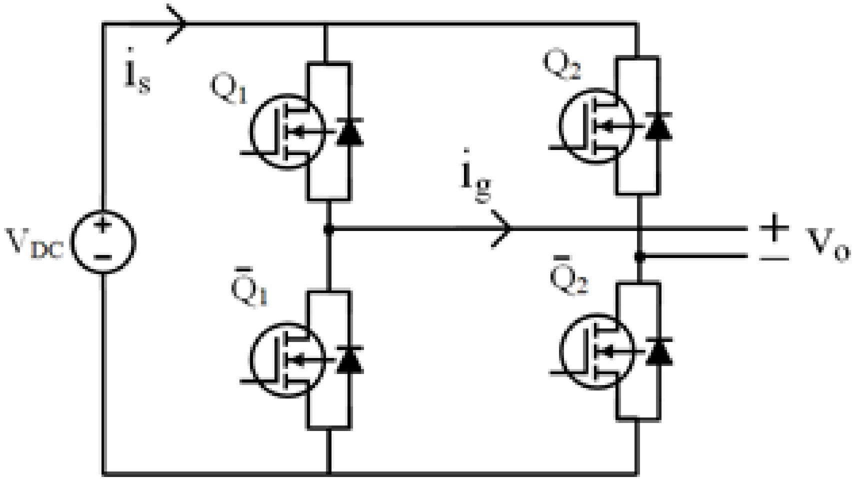


Frequency-Amplitude spectrum of i_s

Quantifying the DC-Link Current – literature review

- Passive solutions: simulations and rules of thumb
- Fundamental work by McGrath and Holmes derives the dc-link current for the PWM-driven half-bridge
- A full-bridge dc link current expression proving its intrinsic properties in a cascaded converter is missing
- This work utilizes its derivation to map the active and reactive grid power requirements to the dc link capacitor's rms current stress

Quantifying the DC-Link Current – building block



$$v_o(t) = M\cos(\omega_o t + \theta_o) \qquad (1)$$

$$i_g(t) = I_g\cos(\omega_o t + \theta_o + \phi) \qquad (2)$$

$$i_s(t) = [s_1(t) - s_2(t)]\,i_g(t) \qquad (3)$$

$$s_1(t) = \frac{1}{2} + \frac{M}{2}\cos(\omega_o t + \theta_o) + \sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty}\frac{2}{m\pi}\left[J_n(m\frac{\pi}{2}M)\cos(m[\omega_c t + \theta_c] + n[\omega_o t + \theta_o])\right] \qquad (5)$$

$$s_2(t) = \frac{1}{2} + \frac{M}{2}\cos(\omega_o t + \theta_o + \pi) + \sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty}\frac{2}{m\pi}\left[J_n(m\frac{\pi}{2}M)\cos(m[\omega_c t + \theta_c] + n[\omega_o t + \theta_o] + \pi)\right] \qquad (6)$$

Quantifying the DC-Link Current – methodology

- Steps to obtain the dc link current due to PWM-driven half-bridge
  - $i_s(t) = s(t) \times i_g(t)$
  - $I_s(\omega) = \mathcal{F}\{i_s(t)\}$

    $$= \mathcal{F}\{s(t)\} * \mathcal{F}\{i_g(t)\}$$

    $$= S(\omega) * I_g(\omega)$$
  - $i_s(t) = \mathcal{F}^{-1}\{I_s(\omega)\}$

DC-Link Current of a PWM-driven full-bridge

$$\mathcal{F}^{-1}\left[S_1(\omega) * I_g(\omega)\right](t) = \frac{MI_g}{4}\cos(\phi) + \frac{I_g}{2}\left[\cos(\omega_o t + \theta_o)\cos(\phi) - \sin(\omega_o t + \theta_o)\sin(\phi)\right] \\ + \frac{MI_g}{4}\left[\cos(2\omega_o t - 2\theta_o)\cos(\phi) + \sin(2\omega_o t - 2\theta_o)\sin(\phi)\right] + \sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty}\frac{I_g}{2}\alpha \tag{7}$$

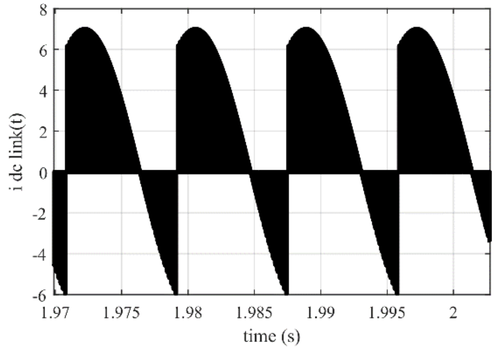
$$\mathcal{F}^{-1}\left[S_2(\omega) * I_g(\omega)\right](t) = -\frac{MI_g}{4}\cos(\phi) + \frac{I_g}{2}\left[\cos(\omega_o t + \theta_o)\cos(\phi) - \sin(\omega_o t + \theta_o)\sin(\phi)\right] \\ - \frac{MI_g}{4}\left[\cos(2\omega_o t - 2\theta_o)\cos(\phi) + \sin(2\omega_o t - 2\theta_o)\sin(\phi)\right] - \sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty}\frac{I_g}{2}\alpha \tag{8}$$

$$i_s(t) = \frac{MI_g}{2}\cos(\phi) + \frac{MI_g}{2}\left[\cos(2\omega_o t - 2\theta_o)\cos(\phi) + \sin(2\omega_o t - 2\theta_o)\sin(\phi)\right] + \sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty} I_g\alpha \tag{9}$$

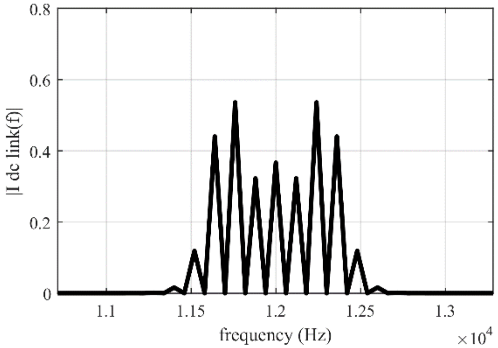
$: \alpha = (K_{m,n+1} + K_{m,n-1})\cos(m[\omega_c t + \theta_c] + n[\omega_o t + \theta_o])\cos(\phi) + (K_{m,n+1} - K_{m,n-1})\sin(m[\omega_c t + \theta_c] + n[\omega_o t + \theta_o])\sin(\phi)$

$: K_{mn} = \frac{2}{m\pi}J_n(m\frac{\pi}{2}M)\sin([m+n]\frac{\pi}{2}).$

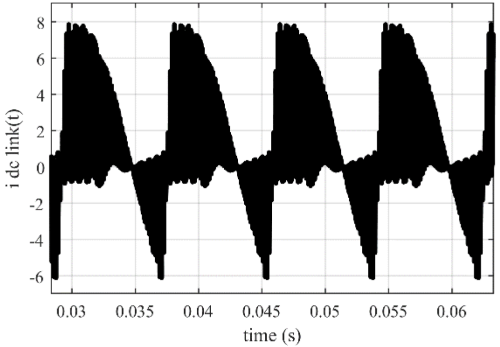
Validation of the derived DC-link current, $i_s(t)$



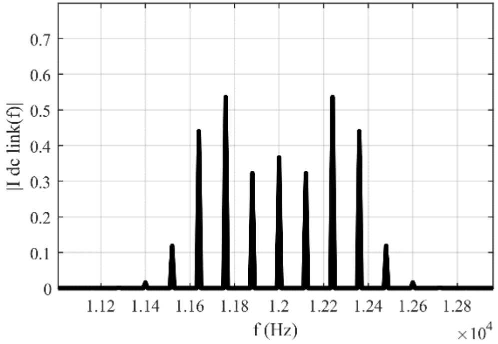
Simulated $i_s(t)$



Simulated $i_s(t)$'s frequency spectrum

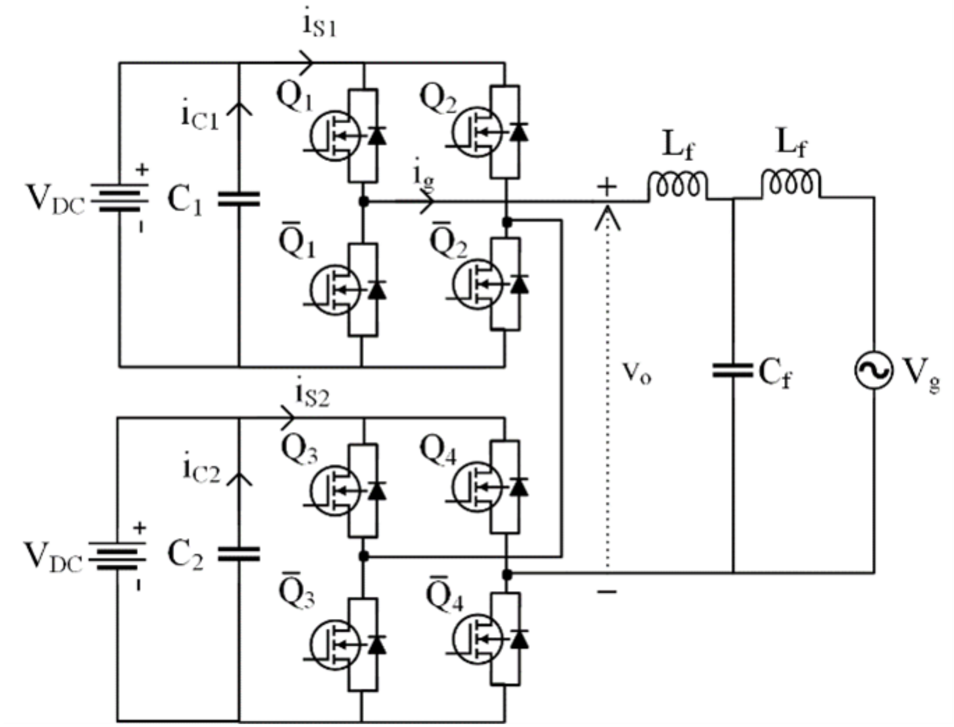


Analytical $i_s(t)$



Analytical $i_s(t)$'s frequency spectrum

Applying the derived $i_s(t)$ to a grid-tied application

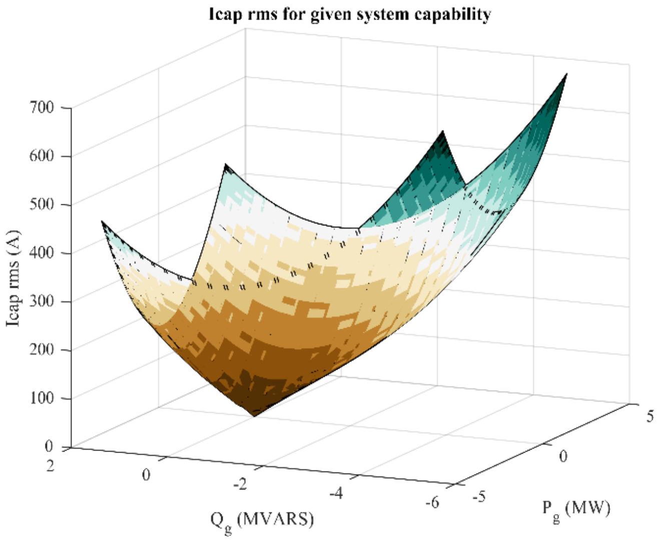


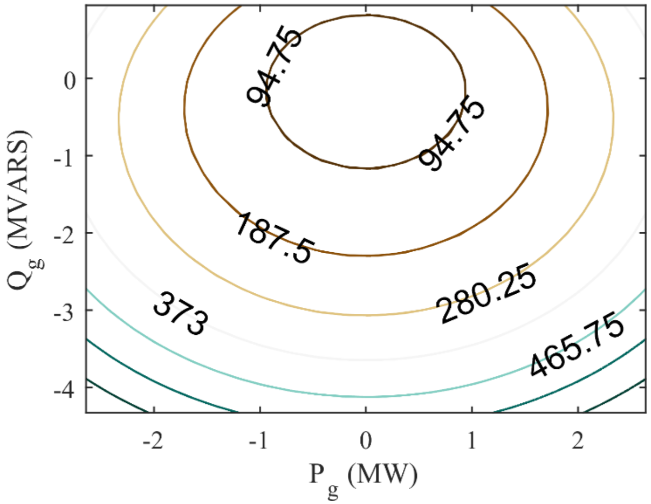
Mapping grid's active and reactive power to DC-link capacitor's rms current stress

$$I^2_{cap,rms} = \left[\frac{1-\omega^2 L_f C_f}{2\left|\hat{V}_g\right|}\right]^2 \left[P_g^2 + \left(Q_g - \frac{\omega C_f \left|\hat{V}_g\right|^2}{1-\omega^2 L_f C_f}\right)^2\right] \left[\frac{\beta}{2V_{DC}^2} + \sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty} \frac{4}{m\pi} \sin([m+n]\frac{\pi}{2}) J\left(\frac{m\pi}{V_{DC}}\sqrt{\beta}\right)^2\right]$$

$$: \beta = \left(\frac{P_g}{\left|\hat{V}_g\right|}(2\omega L_f - \omega^3 L_f^2 C_f)\right)^2 + \left(\frac{Q_g}{\left|\hat{V}_g\right|}(2\omega L_f - \omega^3 L_f^2 C_f) + \left|\hat{V}_g\right|(1-\omega^2 L_f C_f)\right)^2 \quad (10)$$

Various plots of $I_{cap,rms}$ vs P_g vs Q_g





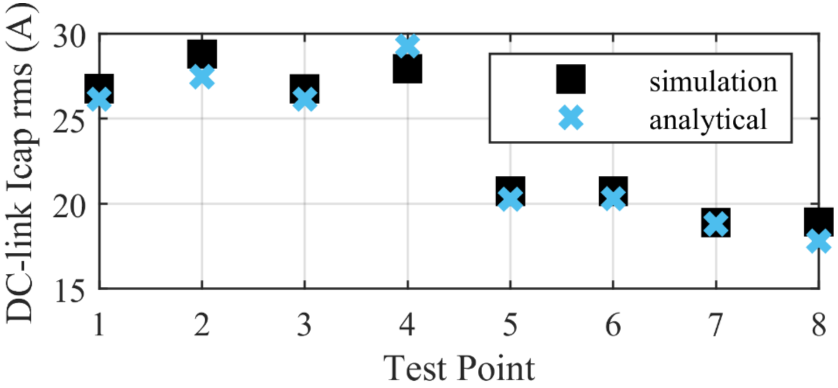
RMS current in the DC link capacitors of each full-bridge under grid's complex power plane

RMS current contours of the DC link capacitors of each full-bridge under grid's complex power plane

Validation of the capacitor stress in the grid-tied system

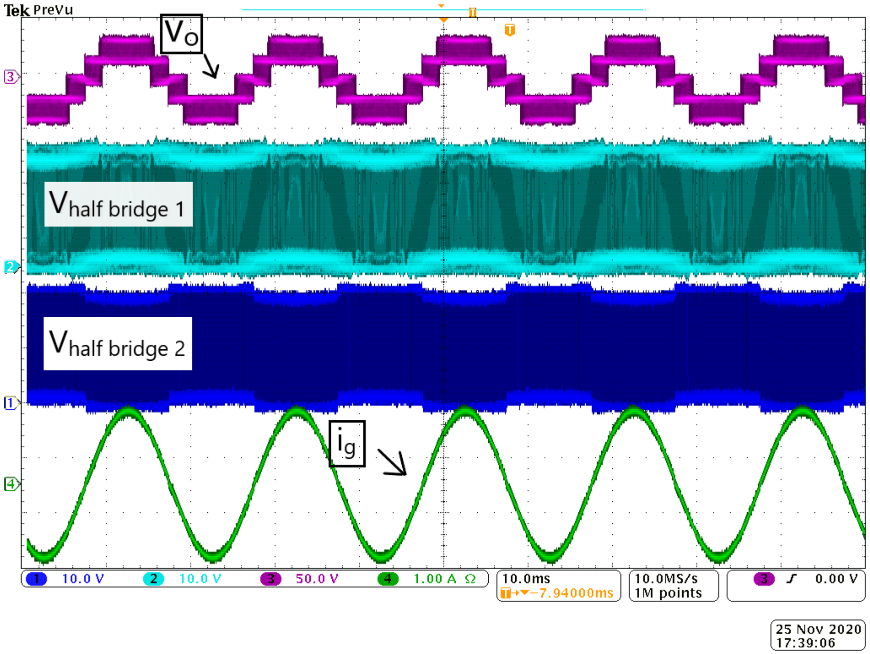
TABLE III
TEST POINTS TO COMPARE SIMULATION AND ANALYTICAL CAPACITOR STRESSES

	1	2	3	4	5	6	7	8
P_g (kW)	321	0	-321	0	-183	183	166	-167
Q_g (kVAR)	5	338	5	-363	168	168	-161	-141

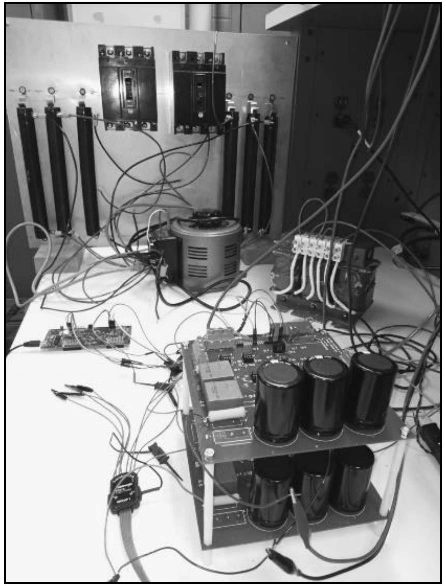


Worst case error: 4.8%

Validation of the framework through low power hardware implementation

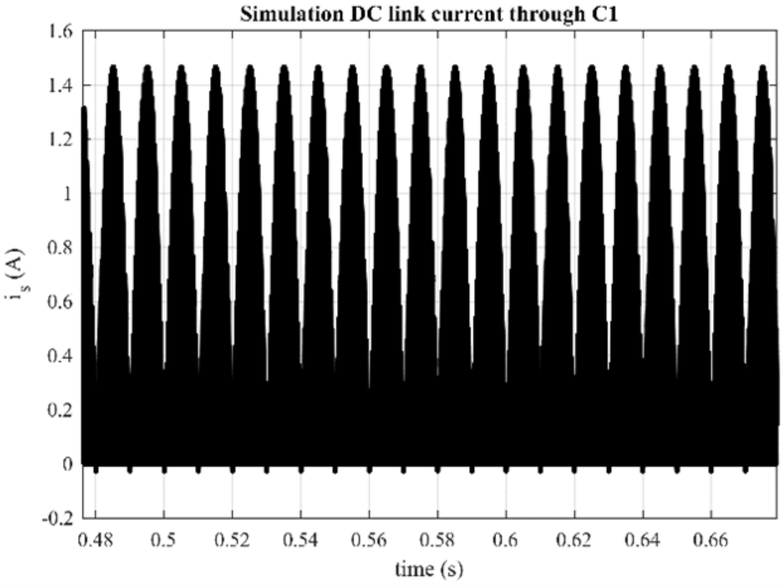


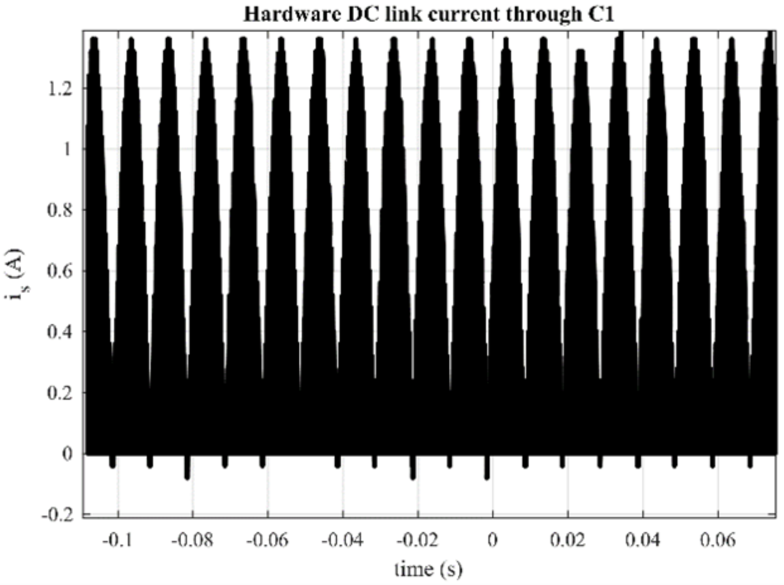
Measured hardware quantities



Hardware prototype with RL load

Validation of the framework through low power hardware implementation





Simulation (left) and hardware (right) worst-case error: 9.2%

Summary

- In this paper, a detailed and exact mathematical model has been developed for the dc-link current in a cascaded H-bridge multilevel converter
- The detail of the model has been used to study the converter's interaction with a grid-tied system
- The grid's active and reactive power commands have been mapped to the dc-link current stress in the bus capacitors
- The analytical, simulation and hardware results have been evaluated in a variety of setups and these show a good match, thereby validating it
- Overall, this work contributes to estimating the lifetime of the dc-link capacitors in an accurate manner which in-turn adds to system reliability by avoiding contingency outages and improving scheduled outages in power systems.

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