

References

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Appendix

The propagation of the small signal perturbation from d_d to i_d and i_q

A three-phase inverter was used as an example for this analysis. In order to simply the derivation process, the dc bus voltage is assumed as a constant; and balanced R-L networks are assumed to be the three-phase load. The system was analyzed based on the operation points as follows:

$$\begin{cases} I_a = I_0 \cos(\omega t + \Phi) \\ I_b = I_0 \cos(\omega t - \frac{2\pi}{3} + \Phi) \\ I_c = I_0 \cos(\omega t + \frac{2\pi}{3} + \Phi) \end{cases}$$

$$\begin{cases} D_a = D_0 \cos(\omega t + \theta) \\ D_b = D_0 \cos(\omega t - \frac{2\pi}{3} + \theta) \\ D_c = D_0 \cos(\omega t + \frac{2\pi}{3} + \theta) \end{cases}$$

$$\begin{cases} D_d = D_{d0} \\ D_q = D_{q0} \end{cases}$$

$$V_c = V_{c0} = \text{const}$$

A perturbation: $\hat{d}_d = d_m \cos(\omega_p t)$ is applied to d channel duty cycle:

$$d_d = D_d + \hat{d}_d = D_{d0} + d_m \cos(\omega_p t)$$

The q channel duty cycle remains the same:

$$d_q = D_{q0}$$

The duty cycles on the ABC coordinates can be written as: (the common-mode component is ignored because it is contribute the three-phase current)

$$\begin{bmatrix} d_a \\ d_b \\ d_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \cos(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{2\pi}{3}) \\ \cos(\omega t + \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} d_d \\ d_q \end{bmatrix}$$

The duty cycle d_a can be written as:

$$\begin{aligned}
d_a &= \cos(\omega t)[D_{d0} + d_m \cos(\omega_p t)] - \sin(\omega t)D_{q0} \\
&= D_a + \frac{2}{3}d_m \cos(\omega t)\cos(\omega_p t) \\
&= D_a + \frac{1}{3}d_m \cos[(\omega + \omega_p)t] \\
&\quad + \frac{1}{3}d_m \cos[(\omega - \omega_p)t]
\end{aligned}$$

Similarly, the db and dc can be written as:

$$\begin{aligned}
d_b &= D_b + \frac{1}{3}d_m \cos[(\omega + \omega_p)t - \frac{2\pi}{3}] \\
&\quad + \frac{1}{3}d_m \cos[(\omega - \omega_p)t - \frac{2\pi}{3}] \quad \text{and} \\
d_c &= D_c + \frac{1}{3}d_m \cos[(\omega + \omega_p)t + \frac{2\pi}{3}] \\
&\quad + \frac{1}{3}d_m \cos[(\omega - \omega_p)t + \frac{2\pi}{3}]
\end{aligned}$$

Because of the following:

$$\begin{bmatrix} d_a v_c \\ d_b v_c \\ d_c v_c \end{bmatrix} = \begin{bmatrix} (D_a + \hat{d}_a)(V_{c0}) \\ (D_b + \hat{d}_b)(V_{c0}) \\ (D_c + \hat{d}_c)(V_{c0}) \end{bmatrix} = \underbrace{\begin{bmatrix} D_a V_{c0} \\ D_b V_{c0} \\ D_c V_{c0} \end{bmatrix}}_{\text{DC points}} + \underbrace{\begin{bmatrix} \hat{d}_a V_{c0} \\ \hat{d}_b V_{c0} \\ \hat{d}_c V_{c0} \end{bmatrix}}_{\text{First Order Term}}$$

DC points + First Order Term

The three-phase currents produced by these two terms are:

$$\left\{ \begin{aligned}
i_a &= I_a + \frac{1}{3} \frac{d_m V_{c0}}{\sqrt{R_L^2 + ((\omega + \omega_p)^2 L^2)}} [\cos(\omega + \omega_p)t + \varphi] \\
&\quad + \frac{1}{3} \frac{d_m V_{c0}}{\sqrt{R_L^2 + ((\omega - \omega_p)^2 L^2)}} [\cos(\omega - \omega_p)t + \varphi'] \\
i_b &= I_b + \frac{1}{3} \frac{d_m V_{c0}}{\sqrt{R_L^2 + ((\omega + \omega_p)^2 L^2)}} [\cos(\omega + \omega_p)t + \varphi - \frac{2\pi}{3}] \\
&\quad + \frac{1}{3} \frac{d_m V_{c0}}{\sqrt{R_L^2 + ((\omega - \omega_p)^2 L^2)}} [\cos(\omega - \omega_p)t + \varphi' - \frac{2\pi}{3}] \\
i_c &= I_c + \frac{1}{3} \frac{d_m V_{c0}}{\sqrt{R_L^2 + ((\omega + \omega_p)^2 L^2)}} [\cos(\omega + \omega_p)t + \varphi + \frac{2\pi}{3}] \\
&\quad + \frac{1}{3} \frac{d_m V_{c0}}{\sqrt{R_L^2 + ((\omega - \omega_p)^2 L^2)}} [\cos(\omega - \omega_p)t + \varphi' + \frac{2\pi}{3}]
\end{aligned} \right.$$

The corresponding d and q channel currents are:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$= \begin{bmatrix} I_d \\ I_q \\ i_0 \end{bmatrix} + \begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta i_0 \end{bmatrix}$$

The d channel current is:

$$\begin{aligned} \hat{i}_d &= \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \cos[(\omega + \omega_p)t + \varphi] \cos(\omega t) \\ &+ \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \cos[(\omega - \omega_p)t + \varphi'] \cos(\omega t) \\ &+ \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \cos[(\omega + \omega_p)t + \varphi - \frac{2\pi}{3}] \cos(\omega t - \frac{2\pi}{3}) \\ &+ \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \cos[(\omega - \omega_p)t + \varphi' - \frac{2\pi}{3}] \cos(\omega t - \frac{2\pi}{3}) \\ &+ \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \cos[(\omega + \omega_p)t + \varphi + \frac{2\pi}{3}] \cos(\omega t + \frac{2\pi}{3}) \\ &+ \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \cos[(\omega - \omega_p)t + \varphi' + \frac{2\pi}{3}] \cos(\omega t + \frac{2\pi}{3}) \\ \hat{i}_d &= \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \left\{ \frac{1}{2} \cos[(2\omega + \omega_p)t + \varphi] + \frac{1}{2} \cos(\omega_p t + \varphi) \right. \\ &\quad \left. + \frac{1}{2} \cos[(2\omega + \omega_p)t + \varphi - \frac{4\pi}{3}] + \frac{1}{2} \cos(\omega_p t + \varphi) \right. \\ &\quad \left. + \frac{1}{2} \cos[(2\omega + \omega_p)t + \varphi + \frac{4\pi}{3}] + \frac{1}{2} \cos(\omega_p t + \varphi) \right\} \\ &+ \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \left\{ \frac{1}{2} \cos[(2\omega - \omega_p)t + \varphi'] + \frac{1}{2} \cos(\omega_p t - \varphi') \right. \\ &\quad \left. + \frac{1}{2} \cos[(2\omega - \omega_p)t + \varphi' - \frac{4\pi}{3}] + \frac{1}{2} \cos(\omega_p t - \varphi') \right. \\ &\quad \left. + \frac{1}{2} \cos[(2\omega - \omega_p)t + \varphi' + \frac{4\pi}{3}] + \frac{1}{2} \cos(\omega_p t - \varphi') \right\} \\ \hat{i}_d &= \frac{1}{2} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \cos(\omega_p t + \varphi) + \frac{1}{2} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \cos(\omega_p t - \varphi') \end{aligned}$$

$$\phi = -\arctg\left[\frac{(\omega + \omega_p)L}{R_L}\right]$$

$$\phi' = \arctg\left[\frac{(\omega_p - \omega)L}{R_L}\right]$$

$$\left| \frac{\hat{i}_d}{d_m} \right| = \frac{V_{c0}}{2} \sqrt{\frac{2}{3}} \sqrt{\frac{1}{R_L^2 + (\omega + \omega_p)^2 L^2} + \frac{1}{R_L^2 + (\omega - \omega_p)^2 L^2} + \frac{2 \cos(\phi + \phi')}{\sqrt{(R_L^2 + (\omega + \omega_p)^2 L^2)(R_L^2 + (\omega - \omega_p)^2 L^2)}}$$

$$\angle \frac{\hat{i}_d}{d_m} = \phi + \arccos\left\{ \frac{\frac{2}{R_L^2 + (\omega + \omega_p)^2 L^2} + \frac{2 \cos(\phi + \phi')}{\sqrt{(R_L^2 + (\omega + \omega_p)^2 L^2)(R_L^2 + (\omega - \omega_p)^2 L^2)}}}{2 \sqrt{\frac{1}{R_L^2 + (\omega + \omega_p)^2 L^2} + \frac{1}{R_L^2 + (\omega - \omega_p)^2 L^2} + \frac{2 \cos(\phi + \phi')}{\sqrt{(R_L^2 + (\omega + \omega_p)^2 L^2)(R_L^2 + (\omega - \omega_p)^2 L^2)}}}} \cdot \frac{1}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \right\}$$

Similarly, the q channel current is:

$$\begin{aligned} \Delta i_q = & -\frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \cos[(\omega + \omega_p)t + \phi] \sin(\omega t) \\ & - \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \cos[(\omega - \omega_p)t + \phi'] \sin(\omega t) \\ & - \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \cos[(\omega + \omega_p)t + \phi - \frac{2\pi}{3}] \sin(\omega t - \frac{2\pi}{3}) \\ & - \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \cos[(\omega - \omega_p)t + \phi' - \frac{2\pi}{3}] \sin(\omega t - \frac{2\pi}{3}) \\ & - \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \cos[(\omega + \omega_p)t + \phi + \frac{2\pi}{3}] \sin(\omega t + \frac{2\pi}{3}) \\ & - \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \cos[(\omega - \omega_p)t + \phi' + \frac{2\pi}{3}] \sin(\omega t + \frac{2\pi}{3}) \end{aligned}$$

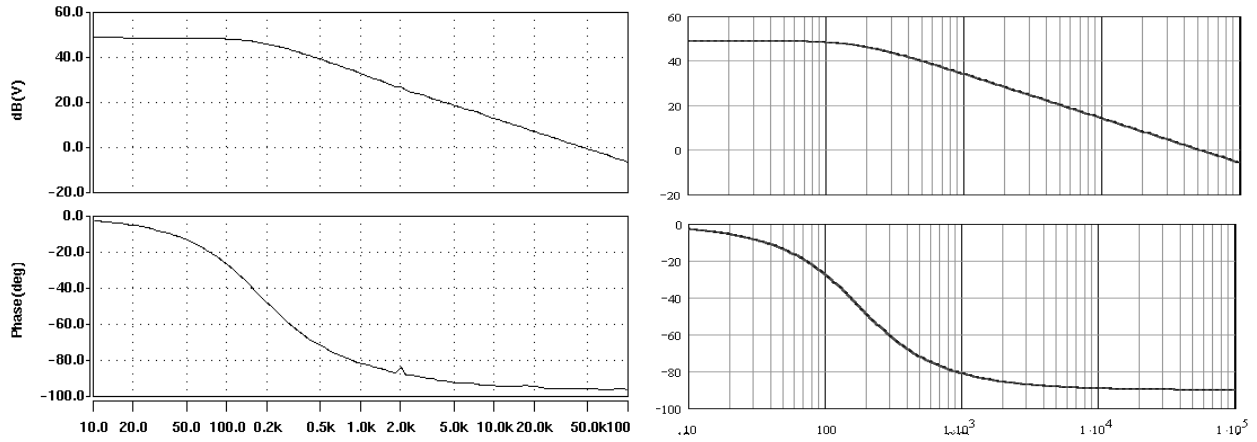
$$\begin{aligned} \hat{i}_q = & -\frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \left\{ \frac{1}{2} \sin[(2\omega + \omega_p)t + \phi] - \frac{1}{2} \sin(\omega_p t + \phi) \right. \\ & + \frac{1}{2} \sin[(2\omega + \omega_p)t + \phi - \frac{4\pi}{3}] - \frac{1}{2} \sin(\omega_p t + \phi) \\ & \left. + \frac{1}{2} \sin[(2\omega + \omega_p)t + \phi + \frac{4\pi}{3}] - \frac{1}{2} \sin(\omega_p t + \phi) \right\} \\ & - \frac{1}{3} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \left\{ \frac{1}{2} \sin[(2\omega - \omega_p)t + \phi'] - \frac{1}{2} \sin(\omega_p t - \phi') \right. \\ & + \frac{1}{2} \sin[(2\omega - \omega_p)t + \phi' - \frac{4\pi}{3}] - \frac{1}{2} \sin(\omega_p t - \phi') \\ & \left. + \frac{1}{2} \sin[(2\omega - \omega_p)t + \phi' + \frac{4\pi}{3}] - \frac{1}{2} \sin(\omega_p t - \phi') \right\} \end{aligned}$$

$$\hat{i}_q = -\frac{1}{2} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \sin(\omega_p t + \phi) + \frac{1}{2} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \sin(\omega_p t - \phi')$$

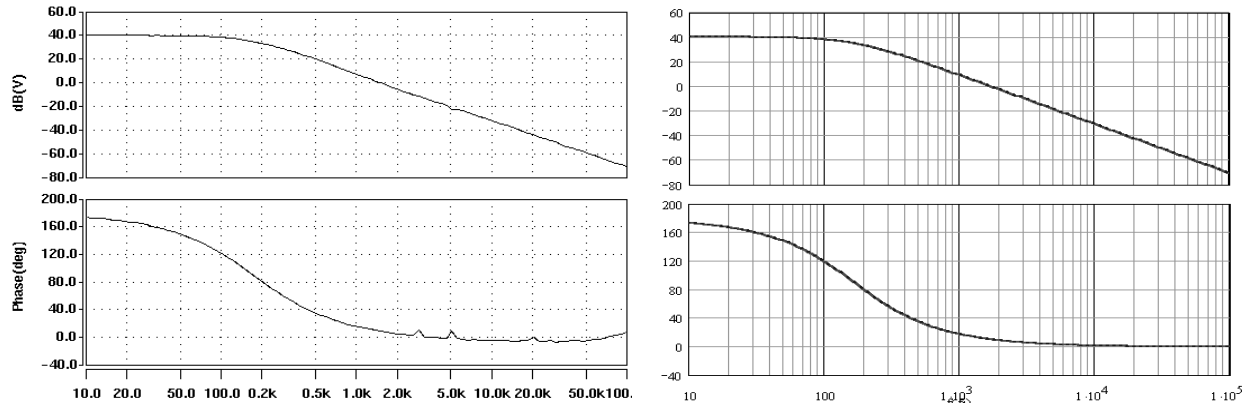
$$\hat{i}_q = \frac{1}{2} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \cos(\omega_p t + \varphi + \frac{\pi}{2}) + \frac{1}{2} \sqrt{\frac{2}{3}} \frac{d_m V_{c0}}{\sqrt{R_L^2 + (\omega - \omega_p)^2 L^2}} \cos(\omega_p t - \varphi' - \frac{\pi}{2})]$$

$$\left| \frac{\hat{i}_q}{d_m} \right| = \frac{V_{c0}}{2} \sqrt{\frac{2}{3}} \sqrt{\frac{1}{R_L^2 + (\omega + \omega_p)^2 L^2} + \frac{1}{R_L^2 + (\omega - \omega_p)^2 L^2} + \frac{-2 \cos(\phi + \phi')}{\sqrt{(R_L^2 + (\omega + \omega_p)^2 L^2)(R_L^2 + (\omega - \omega_p)^2 L^2)}}}$$

$$\angle \frac{\hat{i}_q}{d_m} = \phi + \frac{3\pi}{2} - \arccos\left\{ \frac{\frac{2}{R_L^2 + (\omega + \omega_p)^2 L^2} + \frac{-2 \cos(\phi + \phi')}{\sqrt{(R_L^2 + (\omega + \omega_p)^2 L^2)(R_L^2 + (\omega - \omega_p)^2 L^2)}}}{2 \sqrt{\frac{1}{R_L^2 + (\omega + \omega_p)^2 L^2} + \frac{1}{R_L^2 + (\omega - \omega_p)^2 L^2} + \frac{-2 \cos(\phi + \phi')}{\sqrt{(R_L^2 + (\omega + \omega_p)^2 L^2)(R_L^2 + (\omega - \omega_p)^2 L^2)}}}} \cdot \frac{1}{\sqrt{R_L^2 + (\omega + \omega_p)^2 L^2}} \right\}$$



(a)



(b)

Figure A1 The comparison between the mathematical derivation and the simulation results of the transfer

function $\frac{i_d}{d_d}$, and $\frac{i_q}{d_d}$ of the inverter with R=1 and L=1 mH

VITA

The author was born in Cangxian, Hebei, China, in 1965. He received a B.S. degree from Shannxi Institute of Mechanical Engineering, now the Xian Science and Technology University, in 1986, and a M.S degree from Zhejiang University in 1989, both in Electrical Engineering.

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