References

A. Power Electronics Building Blocks

[A1] Chester Petry, “Shipboard Electrical Power Architecture,” Control Technology Workshop: The Regulation and Distribution of Power in Large Systems, 1995, pp. 102-131.

[A2] Terry Ericsen, Albert Tucker, et.al, “Standardized Power Switch System Modules (Power Electronics Building Blocks),” *PCIM Power Semiconductor Specialists Course Notes, Power Systems World’97*, pp. 5.10-5.30.

[A3] Dan Kinzer, “Intelligent Power Modules as Building Blocks for Power Electronics” *Control Technology Workshop Proceedings*, Blacksburg, Va., April 24-25, 1995, pp. 55-58.

[A4] D. M. Divan, "PEBB Control Issues” *Control Technology Workshop Proceedings*, Blacksburg, Va., April 24-25, 1995, pp. 13-17.

[A5] Fred C. Lee et. al., “PEBBS and System Integration At Virginia Power Electronics Center,” *Government Microcircuit Applications Conference*, March 1997, pp. 419-422.

[A6] K. Xing, R. Lin, F. C. Lee, and D. Borojevic, “Some issues related to Power Electronics Building Blocks,” *VPEC Seminar Proceedings*, 1996, pp. T1-T8.

[A7] Gurjit Thandi, R. Zhang, K. Xing, F. C. Lee, D. Borojevic, “Non-linear Modeling, Simulation and Stability Analysis of dc Distributed Power System,” To be published by *IEEE Transactions on Power Delivery*

[A8] Kun Xing, Gurjit Thandi, Huibin Zhu et al, “Nonlinear Modeling, Control And Stability Analysis of PEBB-Base Power System,” *VPEC Internal Report I-168.*

[A9] “*Power Electronics Building Block and System Integration*”, Project reports with university of Wisconsin -Madison, North Carolina state university/Rensselaer Polytechnic Institute. VPEC, VPI&SU April 1996, 1997, and 1998.

[A.10] Ray L Lin and Fred C. Lee, “Single-Power-Supply-Based Transformerless IGBT/MOSFET Gate Driver with 100% High-Side Turn-on Duty Cycle Operation Performance Using Auxiliary Bootstrapped Charge Pumper,” *IEEE PESC’97*, pp. 1205-1209.

[A11] I. Milosavljevic, *Power Electronics Systems Communications*, Thesis, Virginia Power Electronics Center, VPI&SU, 1999.

B. Packaging and Device Modeling

[B1] Fred Eschrich, “IGBT Modules Simplify Inverter Design,” *PCIM Europe’96*, Jul/Aug, pp. 285-286.

[B2] Bernd Loser, Dieter Brunner et al, “Alternative to DBC for High Power Circuits,” *PCIM Europe’96,* Jul/Aug. 1996, pp. 280-284.

[B3] C. Van Godbold, V. Anand Sankaran and Jerry L. Hudgins, “Novel Design in Power Modules,” *IEEE IAS, 1995*, pp. 911-915.

[B4] Eric Motto, “A New Low Inductance IGBT Module Package,” *Proc. of APET,* Sep. 1996, pp.51-56.

[B5] V. A. Sankaran, C. Chen. C. S. Avant, and X. Xu, “Power Cycling Reliability of IGBT Power Modules,” *IEEE IAS, 1997*, pp. 1222-1228.

[B6] P. Jacob et al, “Reliability Testing and Analysis of IGBT Power Semiconductor Modules,” *Proc. of International Symposium for Testing and Failure Analysis*, 1994, pp. 319-325.

[B7] Hideo Matsuda, Michiaki Hiyoshi, and Noriyasu Kawamura, “Pressure Contact Assembly Technology of High Power Devices,” *ISPSD 1997*, pp. 17-24.

[B8] Shatil Haque, Kun Xing, Ray-Lee Lin, Carlos Suchicital, Guo-Quan Lu, Douglas J. Nelson, Dusan Borojevic, Fred C. Lee, "An Innovative Technique for Packaging Power Electronics Building Blocks Using Metal Posts Interconnected Parallel Plate Structures,” *Proceedings of the 48th IEEE-ECTC Conference*, pp. 922-929, Seattle, WA, May 25-28, 1998.

[B9] K. Xing, Fred C. Lee, and D. Borojevic, “Extraction of Parasitics within Wirebond IGBT Modules,” *IEEE APEC Conference Proceedings*, 1998, pp. 497-503.

[B10] P. Lauritzen, C. L. Ma, “ A Simple Diode Model with Reverse Recovery”, *IEEE on PE’91*, Vol 6, No. 2. pp 188-191.

[B11] IXYS IGBT Data Sheet.

C. Soft-Switching

[C1] R. W. De Doncker and J. P. Lyons. “The Auxiliary Resonant Commutated Pole Converter”, *IEEE IAS’90*, pp 1228-1235.

[C2] J. S. Lai, R. W. Young, Sr. G. W. Ott. Jr., J. W. Mckeever, and F. Z. Peng, “A Delta Configured Auxiliary Resonant Snubber Inverter,” *IEEE Trans. on IA*, Vol. 32, No. 3, May/June 1996, pp. 518-525.

[C3] H. Mao, F. C. Lee, X. Zhou, H. Dai, M. Cosan, and D. Borojevic, “Improved Zero-Current Transition Converters for High Power Applications,” *IEEE Transactions on Industrial Applications*, 1997, Vol. 33, pp. 1220-1232.

[C4] Guichao Hua, and Fred C. Lee. "Soft-switching PWM Converter Technologies," *Journal of Circuits, Systems and Computers*, Vol. 5, No. 4, 1995, pp. 531-558.

[C5] Heping Dai, Kun Xing and Fred C. Lee, "Investigation Of Soft-Switching Techniques For Power Electronics Building Blocks (PEBB), *IEEE APEC Conference Proceedings*, 1998, pp. 633-639

D. Control of Three Phase Systems

[D1] Y. Sato and T. Kataoka, "Simplified Control Strategy to Improve AC-Input-Current Waveform of Parallel-Connected Current-Type PWM Rectifiers," *IEE Proc.-Electr. Power Appl.*, Vol. 142, No. 4, Jul. 1995, pp. 246-254.

[D2] Makoto Hashii, Kenji Kousaka, and Masahiro Kaimoto, "New Approach to a High-Power GTO PWM Inverter for AC Motor Drives," *IEEE Transactions on Industry Applications*, Vol. IA-23, No. 2, 1987, pp. 263-269.

[D3] Juan W. Dixon and Boon T. Ooi, "Series and Parallel Operation of Hysteresis Current-Controlled PWM Rectifiers," *IEEE Transactions on Industry Applications*, Vol. 25, No. 4, 1989, pp. 644-651.

[D4] Takao Kawabata and Shigenori Higashino, "Parallel Operation of Voltage Source Inverters," *IEEE Transactions on Industry Applications*, Vol. 24, No. 2, 1988, pp. 281-287.

[D5] Isao Takahashi and Minoru Yamane, "Multiparallel Asymmetrical Cycloconverter Having Improved Power Factor and Waveforms," *IEEE Transactions on Industry Applications*, Vol. 22, No. 6, 1986, pp.1007-1016.

[D6] Satoshi Ogasawara, Jin Takagaki, Hirofumi Akagi and Akira Nabae, "A Novel Control Scheme of Duplex Current-Controlled PWM Inverters," *IEEE IAS'87*, pp. 330-337.

[D7] Loren H. Walker, "10 MW GTO Converter for Battery Peaking Service," *IEEE Transactions on Industry Applications*, Vol. 26, No. 1, 1990, pp.63-67.

[D8] Thomas G. Habetler, "A Space Vector-Based Rectifier Regulator for AC/DC/AC Converters," *EPE'91*, Vol. 2, pp. 101-107.

[D9] Hengchun Mao, Dusan Borojevic, Ambatiputi Ravindra, and Fred C. Lee, "Analysis and Design of High Frequency Three-Phase Boost Rectifier," *VPEC Seminar Proc.'95*, pp. 195-203.

[D10] Silva Hiti, Dusan Borojevic, and Carlos Cuadros, "Small Signal Modeling and Control of Three-Phase PWM Converters," *IEEE IAS'94*, pp. 1143-1150.

[D11] Zhihong Ye, Kun Xing, Sudip Mazumder, Dusan Borojevic, and Fred. C. Lee, "Modeling and Control of Parallel Three Phase PWM Boost Rectifiers in PEBB-Based dc Distributed Power System," *IEEE APEC'98*, Vol. 2, pp.1126-1132.

[D12] Keiju Matsui, “A Pulsewidth Modulated Inverter with Parallel-Connected Transistors by Using Current Sharing Reactors,” *IEEE IAS’85*, pp.1015-1019.

[D13] V. Himamshu Prasad, Dusan Borojevic, and Stephen Dubovsky, “Comparison of High Frequency PWM Algorithms for Voltage Source Inverters,” *VPEC Seminar Proc.’96***,** pp. 115-122.

[D14] Kun Xing, S. Mazumder, Z. Ye, F. C. Lee, and D. Borojevic, “The Circulating Current In Paralleled Three-Phase Boost PFC Rectifiers,” *IEEE PESC’98*, Vol. 1, pp.783-789.

[D15] H. Mao, D. Borojevich, and F. C. Lee, “Novel Reduced-Order Small-Signal Model of a Three-Phase PWM Rectifier and Its Application in Control Design and System Analysis, *IEEE Transactions on Power Electronics*, Vol. 13, No. 3, May 1998, pp. 511-521.

[D16] H. W. V. D. Broeck et. al. “Analysis and Realization of Pulse Width Modulation Based on Voltage Space Vectors”, *IEEE-IA’88*, Vol 24, No. 1, pp142-150.

[D17] “The Control Handbook,” CRC Press, pp. 388-396.

E. Neutral Voltage Shift Issues

[E1] I. Kerszenbaum, “Shaft Currents in Electric Machines Fed by Solid State Drives,” *Proc. Industrial and Commercial Power System Tech. Conf.*, 1992, pp. 71-79.

[E2] J. Erdman, R. J. Kerkman, D. Schlegel, and G. Skibinski, “Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltages,” *Proc. of 10th APEC*, 1995, Vol. 1, pp. 24-33.

[E3] S. Chen, T. A. Lipo, and D. Fitzgerald, “Source of Induction Motor Bearing Current Caused by PWM Inverters”, *IEEE Trans. on Energy Conversion*, Vol. 11, No. 1 March 1996, pp. 25-32.

[E4] S. Chen, T. A. Lipo and Donald W. Novotny, “Circulating Type Motor Bearing Current in Inverter Drivers,” *IEEE IAS’96*, pp. 162-167.

[E5] H. W. van der Broeck, H. C. Skudelny and G. V. Stanke, “Analysis and realization of a Pulse Width Modulator Based on Voltage Space Vector,” *IEEE Trans. on IA*, Vol. 24, No. 1, Feb, 1988, pp. 142-150.

[E6] S. Bhattacharya, L. Resta, D. M. Divan, D. W. Novotny, and T. A. Lipo, “Experimental Comparison of Motor Bearing Currents with PWM Hard and Soft Switched Voltage Source Inverters,” *IEEE PESC’96*, pp. 1528-11534.

[E7] Doyle Busse, Jay Erdman, Russel J. Kerkman, Dave Schlegel, and Gary Skibinski, “An Evaluation of the Electrostatic Shielded Induction Motor: A Solution of Rotor Shaft Voltage Buildup and Bearing Current,*” IEEE IAS’96*, pp. 610-617.

[E8] A. L. Julian, T. A. Lipo, and G. Oriti, “Elimination of Common Mode Voltage in Three-Phase Sinusoidal Power Converters,” *IEEE PESC’96*, pp. 1969-1972.

F. Distributed Power System

[F1]. R. D. Middlebrook, "Input Filter Considerations in Design and Application of Switching Regulators", *IEEE Industry Applications society Annual Meeting*, 1976 Record. pp 366-382

[F2]. Ray Ridely, and B. H. Cho, "Distributed Power System Part I & II", *High Frequency Power Conversion*, 1992, pp 1-84

[F3] E.W. Gholdston, K. Karimi, F.C. Lee, J. Rajagopalan, Y. Panov, B. Manners, "Stability of Large DC Power Systems Using Switching Converters, with Application to the International Space Station," *31st Intersociety Energy Conversion Engineering Conference IECEC*, August 1996.

[F4] T. J. Hammons, B. W. Tay, K. L. Kok, “Power Links with Ireland-Excitation of Turbine-Generator Shaft Torsional Vibrations by Variable Frequency Currents Superimposed on DC Currents in Asynchronous HVDC Links,” *IEEE Transactions on Power Systems*, 1995, Vol. 10, No. 3, pp. 1572-9.

[F5] T. J. Hammons, J. J. Bremner, “Analysis of Variable-Frequency Currents Superimposed on DC Currents in Asynchronous HVDC Links in Stressing Turbine-Generator-Exciter Shafts,” *IEEE Transactions on Energy Conversion*, 1995, Vol. 10, No. 1, pp. 95-104.

[F6] X. Feng, Z. Ye, K. Xing, F. C. Lee, D. Borojevic, “Individual Load Impedance Specifications for a Stabel DC Distributed Power System,” *IEEE 14th APEC*, 1999.

[F7] K. Xing, F. c. Lee, and D. Borojevic, “Active Compensation of the Pulsating Current in A Distributed Power System,” *VPEC Seminar Proceedings*, Sept. 1998.

[F8] R. Zhang, C. Liu, L. Chen, D. Borojevic, and F. C. Lee, “An Utility Power Supply for Nonlinear and Unbalanced Load in a PEBB-based dc Distributed Power System,” *VPEC Seminar Proceedings*, Sept. 1998.

Appendix

The propagation of the small signal perturbation from dd to id and iq

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:

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

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

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

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

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 da can be written as:

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

Similarly, the db and dc can be written as:

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

Because of the following:

$$\begin{bmatrix} d_a v_c \\ d_b v_c \\ d_c v_c \end{bmatrix} = \begin{bmatrix} (D_a + \hat{d}_a)(V_{c0}) \\ (D_b + \hat{d}_b)(V_{c0}) \\ (D_c + \hat{d}_c)(V_{c0}) \end{bmatrix} = \underbrace{\begin{bmatrix} D_a V_{c0} \\ D_b V_{c0} \\ D_c V_{c0} \end{bmatrix}} + \underbrace{\begin{bmatrix} \hat{d}_a V_{c0} \\ \hat{d}_b V_{c0} \\ \hat{d}_c V_{c0} \end{bmatrix}}$$

DC points + First Order Term

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

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

The corresponding d and q channel currents are:

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

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

The d channel current is:

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

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

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

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

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

$$\boxed{\begin{aligned}
&\left|\frac{\hat{i}_d}{d_m}\right| = \frac{V_{c0}}{2}\sqrt{\frac{2}{3}}\sqrt{\frac{1}{R_L{}^2 + (\omega+\omega_p)^2 L^2} + \frac{1}{R_L{}^2 + (\omega-\omega_p)^2 L^2} + \frac{2\cos(\phi+\phi')}{\sqrt{(R_L{}^2 + (\omega+\omega_p)^2 L^2)(R_L{}^2 + (\omega-\omega_p)^2 L^2)}}} \\
&\angle\frac{\hat{i}_d}{d_m} = \phi + \arccos\{\frac{\frac{2}{R_L{}^2 + (\omega+\omega_p)^2 L^2} + \frac{2\cos(\phi+\phi')}{\sqrt{(R_L{}^2 + (\omega+\omega_p)^2 L^2)(R_L{}^2 + (\omega-\omega_p)^2 L^2)}}}{2\sqrt{\frac{1}{R_L{}^2 + (\omega+\omega_p)^2 L^2} + \frac{1}{R_L{}^2 + (\omega-\omega_p)^2 L^2} + \frac{2\cos(\phi+\phi')}{\sqrt{(R_L{}^2 + (\omega+\omega_p)^2 L^2)(R_L{}^2 + (\omega-\omega_p)^2 L^2)}}} \bullet \frac{1}{\sqrt{R_L{}^2 + (\omega+\omega_p)^2 L^2}}}\}
\end{aligned}}$$

Similarly, the q channel current is:

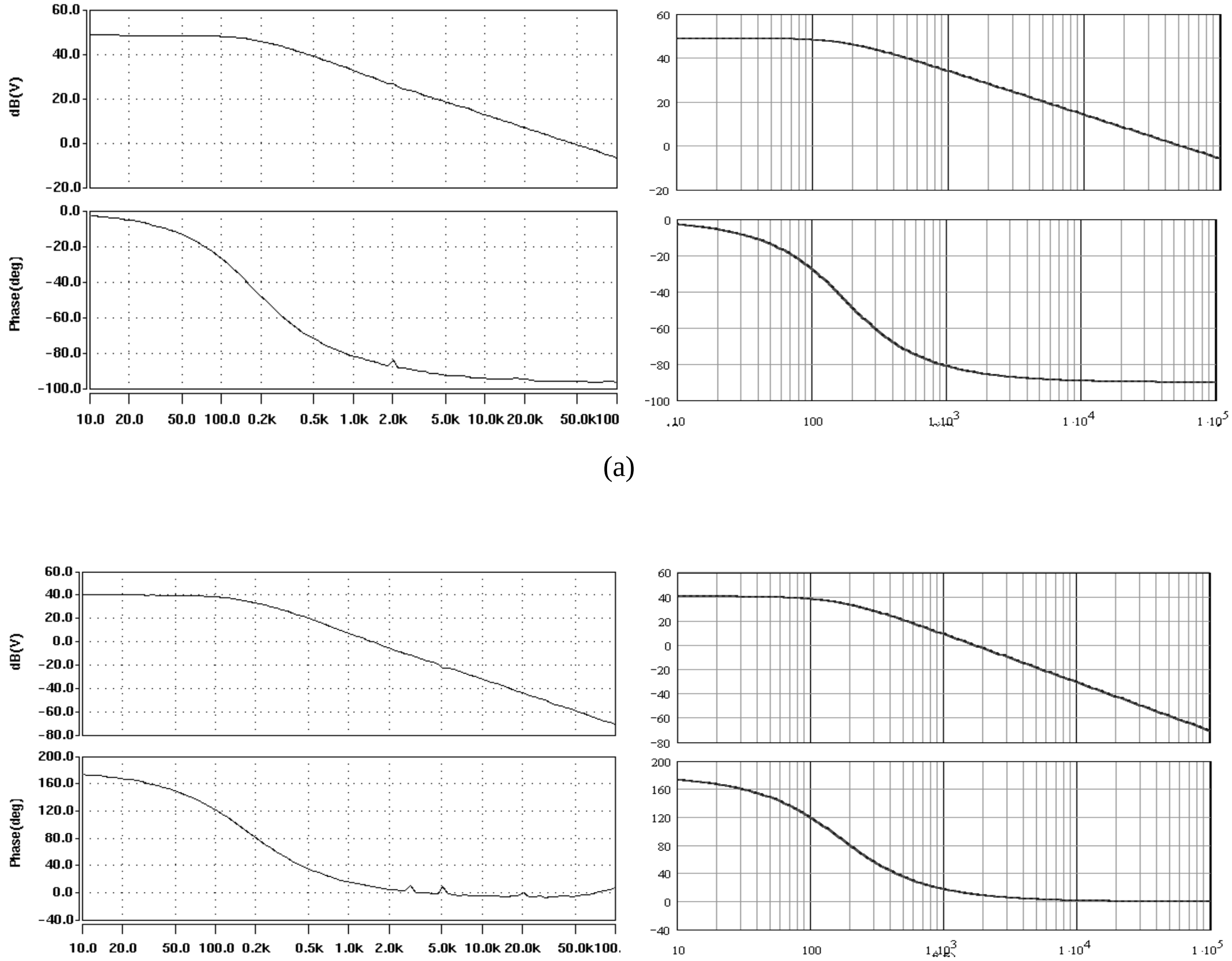
$$\begin{aligned}
\Delta i_q = &-\frac{1}{3}\sqrt{\frac{2}{3}}\frac{d_m V_{c0}}{\sqrt{R_L{}^2 + (\omega+\omega_p)^2 L^2}}\cos[(\omega+\omega_p)t + \varphi]\sin(\omega t) \\
&- \frac{1}{3}\sqrt{\frac{2}{3}}\frac{d_m V_{c0}}{\sqrt{R_L{}^2 + (\omega-\omega_p)^2 L^2}}\cos[(\omega-\omega_p)t + \varphi']\sin(\omega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

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

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

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

$$\boxed{\begin{gathered}
\left|\frac{\hat{i}_q}{d_m}\right| = \frac{V_{c0}}{2}\sqrt{\frac{2}{3}}\sqrt{\frac{1}{R_L{}^2 + (\omega + \omega_p)^2 L^2} + \frac{1}{R_L{}^2 + (\omega - \omega_p)^2 L^2} + \frac{-2\cos(\phi + \phi')}{\sqrt{(R_L{}^2 + (\omega + \omega_p)^2 L^2)(R_L{}^2 + (\omega - \omega_p)^2 L^2)}}} \\[2em]
\angle\frac{\hat{i}_q}{d_m} = \phi + \frac{3\pi}{2} - \arccos\{\frac{\dfrac{2}{R_L{}^2 + (\omega + \omega_p)^2 L^2} + \dfrac{-2\cos(\phi + \phi')}{\sqrt{(R_L{}^2 + (\omega + \omega_p)^2 L^2)(R_L{}^2 + (\omega - \omega_p)^2 L^2)}}}{2\sqrt{\dfrac{1}{R_L{}^2 + (\omega + \omega_p)^2 L^2} + \dfrac{1}{R_L{}^2 + (\omega - \omega_p)^2 L^2} + \dfrac{-2\cos(\phi + \phi')}{\sqrt{(R_L{}^2 + (\omega + \omega_p)^2 L^2)(R_L{}^2 + (\omega - \omega_p)^2 L^2)}}} \bullet \dfrac{1}{\sqrt{R_L{}^2 + (\omega + \omega_p)^2 L^2}}}\}
\end{gathered}}$$



(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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