



































































Example: State-Space Equations – Solution  

$$\vec{i}(t) = e^{-\mathbf{L}^{-1}\mathbf{R}\cdot t} \cdot \vec{i}(0) + \int_{0}^{t} e^{-\mathbf{L}^{-1}\mathbf{R}\cdot(t-\tau)} \cdot \mathbf{L}^{-1} \cdot \vec{v}(\tau) \cdot d\tau$$
Natural Response  

$$\vec{i}(t) = \begin{bmatrix} \dot{i}_{a}(0) \\ \dot{i}_{b}(0) \\ \dot{i}_{c}(0) \end{bmatrix} \cdot e^{-\frac{R}{L}\cdot t} + \frac{V_{m}}{Z} \cdot \begin{bmatrix} \cos(\omega t - \phi) - \frac{R}{Z} \cdot e^{-\frac{R}{L}\cdot t} \\ \cos(\omega t - \frac{2\pi}{3} - \phi) + \frac{R + \sqrt{3} \cdot \omega L}{2Z} \cdot e^{-\frac{R}{L}\cdot t} \\ \cos(\omega t + \frac{2\pi}{3} - \phi) + \frac{R - \sqrt{3} \cdot \omega L}{2Z} \cdot e^{-\frac{R}{L}\cdot t} \end{bmatrix}$$
where per-phase impedance, **Z**, at the source frequency,  $\omega$ , is defined as:  

$$\mathbf{Z} = R + \mathbf{j}\omega L = Z \cdot e^{\mathbf{j}\phi} \qquad Z = \sqrt{R^{2} + \omega^{2}L^{2}} \qquad \phi = \arctan\frac{\omega L}{R}$$





















CPES	G Outline PECon 2008
1.	Introduction
2.	Switching Modeling and PWM
	<ul> <li>Switching model of VSI &amp; boost rectifier</li> </ul>
	<ul> <li>Space vector modulation for VSI &amp; boost rectifier</li> </ul>
	<ul> <li>Other modulations for VSI &amp; boost rectifier</li> </ul>
	<ul> <li>Switching model and modulation for CSI &amp; buck rectifier</li> </ul>
3.	Average Modeling
4.	Small-Signal Modeling
5.	Closed-Loop Control Design
6.	More Complex Converters















































Modulation Index	
For all the switching state vectors, $  V_N   = \sqrt{2} \cdot V_{dc}$ and $\rho = \sqrt{\frac{3}{2}} \cdot V_m$ $d_{vc} = \frac{V_m}{2} \cdot \sin(60^\circ - \phi)$	
$d_N = \frac{V_{dc}}{V_{dc}} \cdot \sin \phi$ $d_{N+1} = \frac{V_m}{V_{dc}} \cdot \sin \phi$	
$d_o = 1 - d_N - d_{N+I}$ $rightarrow$ Define the modulation index $M = \frac{V_m}{V_{dc}}$	
$d_{N} = M \cdot \sin(60^{\circ} - \phi)$ $d_{N+I} = M \cdot \sin \phi$ $d_{0} = I - d_{N} - d_{N+I}$	
DB-	3-70


























CPES	G Outline PECon 2008
1.	Introduction
2.	Switching Modeling and PWM
	<ul> <li>Switching model of VSI &amp; boost rectifier</li> </ul>
	<ul> <li>Space vector modulation for VSI &amp; boost rectifier</li> </ul>
	<ul> <li>Other modulations for VSI &amp; boost rectifier</li> </ul>
	<ul> <li>Switching model and modulation for CSI &amp; buck rectifier</li> </ul>
3.	Average Modeling
4.	Small-Signal Modeling
5.	Closed-Loop Control Design
6.	More Complex Converters



































	G Outline PECon 2008
1.	Introduction
2.	Switching Modeling and PWM
	<ul> <li>Switching model of VSI &amp; boost rectifier</li> </ul>
	<ul> <li>Space vector modulation for VSI &amp; boost rectifier</li> </ul>
	<ul> <li>Other modulations for VSI &amp; boost rectifier</li> </ul>
	<ul> <li>Switching model and modulation for CSI &amp; buck rectifier</li> </ul>
3.	Average Modeling
4.	Small-Signal Modeling
5.	Closed-Loop Control Design
6.	More Complex Converters













$\vec{v}_{L-L} = \begin{bmatrix} v_{AB} \\ v_{BC} \\ v_{CA} \end{bmatrix}  \vec{v}_{l-l} = \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix}  \vec{i}_{l-l} = \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix}  \vec{s}_{l-l} = \begin{bmatrix} s_{ab} \\ s_{bc} \\ s_{ca} \end{bmatrix}$ $\frac{d\vec{i}_{l-l}}{dt} = \frac{1}{3L} \vec{v}_{L-L} - \frac{1}{3L} \vec{v}_{l-l} \qquad \vec{v}_{l-l} = \vec{s}_{l-l} \cdot v_{dc}$ $\frac{dv_{dc}}{dt} = \frac{1}{C} i_{dc} - \frac{v_{dc}}{RC} \qquad i_{dc} = \vec{s}_{l-l}^T \cdot \vec{i}_{l-l}$
$\frac{d\vec{i}_{l-l}}{dt} = \frac{1}{3L}\vec{v}_{L-L} - \frac{1}{3L}\vec{v}_{l-l} \qquad \vec{v}_{l-l} = \vec{s}_{l-l} \cdot v_{dc}$ $\frac{dv_{dc}}{dt} = \frac{1}{C}\vec{i}_{dc} - \frac{v_{dc}}{RC} \qquad \vec{i}_{dc} = \vec{s}_{l-l}^T \cdot \vec{i}_{l-l}$
$\frac{d\vec{i}_{l-l}}{dt} = \frac{1}{3L}\vec{v}_{L-L} - \frac{1}{3L}\vec{s}_{l-l}\cdot v_{dc}$ $\frac{dv_{dc}}{dt} = \frac{1}{C}\vec{s}_{l-l}^T\cdot\vec{i}_{l-l} - \frac{v_{dc}}{RC}$



$$\overrightarrow{v_{ab}} = \overrightarrow{s_{ab}} \cdot \overrightarrow{v_{dc}}$$

$$\overrightarrow{v_{ab}} = \frac{1}{T} \int_{t-T}^{t} \overrightarrow{s_{ab}}(\tau) \cdot \overrightarrow{v_{dc}}(\tau) d\tau \approx \overrightarrow{s_{ab}} \cdot \overrightarrow{v_{dc}} = d_{ab} \cdot \overrightarrow{v_{dc}}$$
if maximum-frequency components of  $v_{dc}(t)$  are  $<<1/2T$ .
$$\overrightarrow{s_{l-l}} \cdot \overrightarrow{v_{dc}} \approx \overrightarrow{s_{l-l}} \cdot \overrightarrow{v_{dc}} = \overrightarrow{d_{l-l}} \cdot \overrightarrow{v_{dc}}$$

$$\overrightarrow{\overline{s_{l-l}}} \cdot \overrightarrow{\overline{l_{l-l}}} \approx \overrightarrow{\overline{s_{l-l}}} \cdot \overrightarrow{\overline{l_{l-l}}} = \overrightarrow{d_{l-l}} \cdot \overrightarrow{\overline{l_{l-l}}}$$
DB-111



























CPES	Coordinate Transformation	
Using	g the following trigonometric relationships	
	$\cos^2 x + \cos^2(x - \frac{2\pi}{3}) + \cos^2(x + \frac{2\pi}{3}) = \frac{3}{2}$	
	$\sin^2 x + \sin^2 (x - \frac{2\pi}{3}) + \sin^2 (x + \frac{2\pi}{3}) = \frac{3}{2}$	
	$\sin x \cdot \cos x + \sin(x - \frac{2\pi}{3}) \cdot \cos(x - \frac{2\pi}{3}) + \sin(x + \frac{2\pi}{3}) \cdot \cos(x + \frac{2\pi}{3}) = 0$	
	$\cos x + \cos(x - \frac{2\pi}{3}) + \cos(x + \frac{2\pi}{3}) = 0$	
	$\sin x + \sin(x - \frac{2\pi}{3}) + \sin(x + \frac{2\pi}{3}) = 0$	
		DB-126

Coordinate Transformation	l
$\square \qquad T \cdot \frac{dT^{-1}}{dt} = \begin{bmatrix} 0 & -\omega & 0 \\ \omega & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	
Therefore: $\int T \frac{dT^{-1}}{dt} \cdot \vec{i}_{dq0} + \frac{d\vec{i}_{dq0}}{dt} = \frac{1}{3L} \vec{v}_{dq0} - \frac{1}{3L} \vec{d}_{dq0} \cdot \vec{v}_{dc}$	
$\frac{d\overline{v}_{dc}}{dt} = \frac{1}{C}\vec{d}_{dq0}^T \cdot \vec{i}_{dq0} - \frac{\overline{v}_{dc}}{RC}$	
$\begin{cases} \frac{d\vec{i}_{dq0}}{dt} = \frac{1}{3L}\vec{v}_{dq0} - \begin{bmatrix} 0 & -\omega & 0\\ \omega & 0 & 0\\ 0 & 0 & 0 \end{bmatrix} \cdot \vec{i}_{dq0} - \frac{1}{3L}\vec{d}_{dq0} \cdot \vec{v}_{dq0} \cdot v$	lc
$\frac{d\overline{v}_{dc}}{dt} = \frac{1}{C}\vec{d}_{dq0}^T \cdot \vec{\bar{i}}_{dq0} - \frac{\overline{v}_{dc}}{RC}$	DB-127

















Linearization
Autonomous dynamic system: $\frac{d\vec{x}}{dt} = \vec{f}(\vec{x}, \vec{u})$
If $\vec{f}$ is analytic it can be expressed as Taylor series:
$\vec{f}(\vec{x},\vec{u}) = \vec{f}(\vec{x}_0,\vec{u}_0) + \frac{\partial \vec{f}(\vec{x}_0,\vec{u}_0)}{\partial \vec{x}} \cdot (\vec{x} - \vec{x}_0) + \frac{\partial \vec{f}(\vec{x}_0,\vec{u}_0)}{\partial \vec{u}} \cdot (\vec{u} - \vec{u}_0) + $
$+\frac{1}{2!}\left[\frac{\partial^{2}\vec{f}(\vec{x}_{0},\vec{u}_{0})}{\partial\vec{x}^{2}}(\vec{x}-\vec{x}_{0})^{2}+\frac{\partial^{2}\vec{f}(\vec{x}_{0},\vec{u}_{0})}{\partial\vec{x}\partial\vec{u}}(\vec{x}-\vec{x}_{0})(\vec{u}-\vec{u}_{0})+\frac{\partial^{2}\vec{f}(\vec{x}_{0},\vec{u}_{0})}{\partial\vec{u}^{2}}(\vec{u}-\vec{u}_{0})^{2}\right]$
+ Retaining the first 3 terms results in linear approximation of $\vec{f}$ :
$\vec{f}(\vec{x},\vec{u}) \cong \vec{f}(\vec{x}_0,\vec{u}_0) + \frac{\partial \vec{f}(\vec{x}_0,\vec{u}_0)}{\partial \vec{x}} \cdot (\vec{x} - \vec{x}_0) + \frac{\partial \vec{f}(\vec{x}_0,\vec{u}_0)}{\partial \vec{u}} \cdot (\vec{u} - \vec{u}_0)$
But the dynamic system is <b>NOT</b> linear because:
$\frac{d\vec{x}}{dt} \cong \frac{\partial \vec{f}(\vec{x}_0, \vec{u}_0)}{\partial \vec{x}} \cdot \vec{x} + \frac{\partial \vec{f}(\vec{x}_0, \vec{u}_0)}{\partial \vec{u}} \cdot \vec{u} + \vec{f}(\vec{x}_0, \vec{u}_0) - \frac{\partial \vec{f}(\vec{x}_0, \vec{u}_0)}{\partial \vec{x}} \cdot \vec{x}_0 - \frac{\partial \vec{f}(\vec{x}_0, \vec{u}_0)}{\partial \vec{u}} \cdot \vec{u}_0$
$\vec{x} = \mathbf{A}  \vec{x} + \mathbf{B}  \vec{u} + \underbrace{\vec{g} \neq 0}_{\text{DB-13i}}$

$$\begin{array}{c} \overbrace{d\vec{x}}{dt} = \vec{f}(\vec{x},\vec{u}) &\cong \vec{f}(\vec{x}_{0},\vec{u}_{0}) + \frac{\partial \vec{f}(\vec{x}_{0},\vec{u}_{0})}{\partial \vec{x}} \cdot (\vec{x} - \vec{x}_{0}) + \frac{\partial \vec{f}(\vec{x}_{0},\vec{u}_{0})}{\partial \vec{u}} \cdot (\vec{u} - \vec{u}_{0}) \\ 
\begin{array}{c} \text{If} (\vec{x}_{0},\vec{u}_{0}) \text{ is an equilibrium point } (\vec{X},\vec{U}), \text{ and } (\tilde{x},\tilde{\vec{u}}) \text{ is perturbation around it:} \\ \hline \Rightarrow & \vec{f}(\vec{X},\vec{U}) \equiv 0 & \vec{x} = \vec{X} + \vec{x} & \vec{u} = \vec{U} + \vec{u} \\ \hline \Rightarrow & \frac{d\vec{X}}{dt} = 0 & \overrightarrow{dt} = \frac{d\vec{X}}{dt} + \frac{d\vec{x}}{dt} = \frac{d\vec{X}}{dt} \\ \hline \Rightarrow & \frac{d\vec{X}}{dt} \equiv \frac{\partial \vec{f}(\vec{x},\vec{u})}{\partial \vec{x}} \Big|_{(\vec{x},\vec{U})} \cdot \vec{x} + \frac{\partial \vec{f}(\vec{x},\vec{u})}{\partial \vec{u}} \Big|_{(\vec{x},\vec{U})} \cdot \vec{u} \\ \hline \Rightarrow & \begin{array}{c} & \dot{\vec{x}} = \mathbf{A} \cdot \vec{x} + \mathbf{B} \cdot \vec{u} \\ \mathbf{A} = \frac{\partial \vec{f}(\vec{x},\vec{u})}{\partial \vec{x}} \Big|_{(\vec{x},\vec{U})} & \mathbf{B} = \frac{\partial \vec{f}(\vec{x},\vec{u})}{\partial \vec{u}} \Big|_{(\vec{x},\vec{U})} \\ \hline \end{array} \right. \end{aligned}$$



$$\begin{array}{c} \overbrace{d}{dt}\left[\overset{\overline{i}_{d}}{\overline{i}_{q}}\right] = \frac{1}{3L}\left[\overset{\overline{v}_{d}}{\overline{v}_{q}}\right] - \left[\begin{smallmatrix}0 & -\omega\\\omega & 0\end{smallmatrix}\right] \cdot \left[\overset{\overline{i}_{d}}{\overline{i}_{q}}\right] - \frac{1}{3L}\left[\begin{smallmatrix}d_{d}\\d_{q}\end{smallmatrix}\right] \cdot \overrightarrow{v}_{dc} \\ \begin{array}{c} \underset{d\overline{v}_{dc}}{Linearization} \\ \frac{d\overline{v}_{dc}}{dt} = \frac{1}{C}\left[d_{d} \quad d_{q}\right] \cdot \left[\overset{\overline{i}_{d}}{\overline{i}_{q}}\right] - \frac{\overrightarrow{v}_{dc}}{RC} \\ \end{array}$$

$$\begin{cases}
\begin{array}{c} \frac{d}{dt}\left[\overset{\overline{i}_{d}}{\overline{i}_{q}}\right] = \frac{1}{3L}\left[\overset{\overline{v}_{d}}{\overline{v}_{q}}\right] - \left[\begin{smallmatrix}0 & -\omega\\\omega & 0\end{smallmatrix}\right] \cdot \left[\overset{\overline{i}_{d}}{\overline{i}_{q}}\right] - \frac{1}{3L}\left[\overset{\overline{d}_{d}}{\overline{d}_{q}}\right] \cdot V_{dc} - \frac{1}{3L}\left[\begin{matrix}D_{d}\\D_{q}\end{array}\right] \cdot \overrightarrow{v}_{dc} \\ \\ \frac{d\widetilde{v}_{dc}}{dt} = \frac{1}{C}\left[\widetilde{d}_{d} \quad \widetilde{d}_{q}\right] \cdot \left[\overset{I_{d}}{I_{q}}\right] + \frac{1}{C}\left[D_{d} \quad D_{q}\right] \cdot \left[\overset{\overline{i}_{d}}{\overline{i}_{q}}\right] - \frac{\widetilde{v}_{dc}}{RC} \\ \end{array}$$
DB-139




















	S Outline	PECon 2008
1.	Introduction	
2.	Switching Modeling and PWM	
3.	Average Modeling	
4.	Small-Signal Modeling	
	<ul> <li>Small-signal model of boost rectifier</li> </ul>	
	<ul> <li>Small-signal model of VSI</li> </ul>	
	<ul> <li>Three-phase modulator modeling</li> </ul>	
5.	Closed-Loop Control Design	
6.	More Complex Converters	DB-150































































	G Outline	PECon 2008
1.	Introduction	
2.	Switching Modeling and PWM	
3.	Average Modeling	
4.	Small-Signal Modeling	
5.	Closed-Loop Control Design	
	Control approach	
	Current-loop design	
	<ul> <li>Voltage-loop design</li> </ul>	
	• Limiting	
6.	More Complex Converters	DB-182











	G Outline	PECon 2008
1.	Introduction	
2.	Switching Modeling and PWM	
3.	Average Modeling	
4.	Small-Signal Modeling	
5.	Closed-Loop Control Design	
6.	More Complex Converters	
	• Three-phase four-wire (four-phase) converter	
	Multilevel converters	
	Parallel converters	
		DB-188





























Dushan Boroyevich: Modeling and Control of Three-Phase PWM Converters Tutorial at PECon 2008, Johor Bahru, Malaysia, 30 November 2008




























































































## Some References

- 1. C. T. Chen, *Linear system theory and design*, 3<sup>rd</sup> ed., New York, NY: Oxford University Press, 1999.
- 2. W. J. Rugh, *Linear system theory*, 2<sup>nd</sup> ed., Englewood Cliffs, NJ.: Prentice Hall, 1996.
- John S. Bay, *Fundamentals of linear state space systems*, New York, NY: McGraw-Hill, 1999. Chapter 2, "Vectors and vector spaces" Chapter 3, "Linear operation on vector spaces"
- 4. D. G. Holmes and T. A. Lipo, *Pulse Width Modulation for Power Converters: Principles and Practice*, New York, NY: IEEE Press and John Wiley & Sons, 2003.
- R. Krishnan, *Electric motor drives: modeling, analysis, and control*, Upper Saddle River, NJ: Prentice Hall, 2001. Chapter 5, "Polyphase induction machines" Chapter 7, "Frequency controlled induction motor drives"
- 6. Paul C. Krause, *Analysis of electric machinery*, Chapter 3, "Reference-frame theory"
- 7. Vincent Del Toro, *Electric power systems*, Chapter 8, "Parameters of electric power systems: a description in terms of symmetrical components"
- 8. Silva Hiti, Modeling and control of three-phase PWM converters, Ph.D. Dissertation, Virginia Tech, 1995.
- 9. P. T. Krein, J. Bentsman, R. M. Bass, and B. Lesieture, "On the use of averaging for the analysis of power electronic systems," *IEEE Trans. Power Electr.*, vol. 5, no. 5, 1990, pp. 182-190.
- 10. R. D. Middlebrook, and S. Cuk, "A general unified approach to modeling switching-converter power stages," *IEEE PESC'76, Rec.*, 1976, pp. 18-34.
- 11. G. W. Wester, and R. D. Middlebrook, "Low-frequency characterization of switched dc-dc converters," *IEEE PESC'72, Rec.*, 1972, pp. 9-20.
- 12. C. T. Rim, D. Y. Hu, and G. H. Cho, "Transformers as equivalent circuits for switches: General proofs and D-Q transformation-based analyses," *IEEE Trans. Ind. Appl.*, vol. 26, no. 4, 1990, pp. 777-785.
- 13. J. M. Noworolski, and S. R. Sanders, "Generalized in-place circuit averaging," *IEEE PESC'91, Rec.*, 1991, pp. 445-450.
- 14. S. R. Sanders, J. M. Noworolski, X. Z. Liu, and G. C. Verghese, "Generalized averaging method for power conversion circuits," *IEEE Trans. Power Electr.*, vol. 6, no. 2, 1991, pp. 251-259.
- 15. K. D. T. Ngo, *Topology and analysis in PWM inversion, rectification, and cycloconversion*, Ph.D. Dissertation, California Institute of Technology, Pasadena, CA, 1984.
- 16. K. D. T. Ngo, "Low frequency characterization of PWM converters," *IEEE Trans. Power Electron.*," vol. PE-1, 1986. pp. 223-230.
- 17. P. Bauer, and J. B. Klaassens, "Dynamic modelling of AC power converters," *IEEE PCC 1993 Rec.*, pp. 502-507, 1993.
- 18. S. Hiti, and D. Borojevic, "Small-signal modeling and control of three-phase PWM converters," 1994 IEEE IAS Annu. Meet., Conf. Rec., 1994.
- 19. R. H. Park, "Two-reaction theory of synchronous machines I and II," *AIEE Trans.*, vol. 48, and vol. 52, 1929 and 1933.
- 20. H. Mao, D. Boroyevich, and F. C. Lee, "Novel reduced-order small-signal model of three-phase PWM rectifier," PESC'96.
- 21. D. M. Brod, and D. W. Novotny, "Current control of VSI-PWM inverters," *IEEE Trans. Industry Appl.*, vol. IA-21, 1985, pp. 562-570.
- 22. Wu, S. B Dewan, and G. R. Slemon, "A PWM Ac-to-DC converter with fixed switching frequency," *IEEE Trans. Industry Appl.*, vol. 26, 1990, pp. 880-885.

- 23. T. G. Habetler, "A space vector-based rectifier regulator for AC/DC/AC converters," *IEEE Trans. Power Electron.*, vol. 8, 1993, pp. 30-36.
- 24. R. Wu, S. B Dewan, and G. R. Slemon, "Analysis of an ac-to-dc voltage source converter using PWM with phase and amplitude control," *IEEE Trans. Industry Appl.*, vol. 27, 1991, pp. 355-363.
- 25. J. W. Dixon, and B T. Ooi, "Indirect current control of a unity power factor sinusoidal current boost type three-phase rectifier," *IEEE Trans. Industrial Electron.*, vol. 35, 1988, pp. 508-515.
- 26. Y. Jiang, F. C. Lee, and D. Borojevic, "Simple high performance three-phase boost rectifiers," *IEEE PESC'94, Rec.*, vol. 2, 1994, pp. 1158-1164.
- 27. H. Sugimoto, S. Morimoto, and M. Yano, "A high-performance control method of a voltage-type PWM converter," *IEEE PESC'88, Rec.*, 1988, pp. 360-368.
- 28. J. W. Kolar, H. Ertl, K. Edelmoser, F. C. Zach, "Analysis of the control behavior of a bidirectional threephase PWM rectifier system," *EPE '91*, vol. 2, 1991, pp. 95-100.
- 29. T. Kawabata, T. Miyashita, and Y. Yamamoto, "Digital control of three-phase PWM inverter with L-C filter," *IEEE PESC'88, Rec.*, 1988, pp. 634-643.
- 30. S. Hiti, and D. Borojevic, "Control of front-end three-phase boost rectifier," *IEEE APEC'94, Conf. Proc.*, vol. 2, 1994, pp.927-933.
- K. Biswas, M. S. Mahesh, B S. R. Iyengar, "A three-phase GTO AC to DC converter with input displacement factor and output voltage control," *1987 IEEE IAS Annu. Meet. Conf. Rec.*, 1987, pp. 685-690.
- 32. Y. Sato, and T. Kataoka, "State feedback control of current type PWM ac-to-dc converter," *1991 IEEE IAS Annu. Meet. Conf. Rec.*, 1991, pp. 840-846.
- 33. Busse, and J. Holtz, "Multiloop control of a unity power factor fast switching ac to dc converter," *IEEE PESC'82, Rec.*, 1982, pp. 171-179.
- 34. S. Hiti, D. Borojevic, F. C. Lee, B. Choi, and S. Lee, "Small-signal modeling of three-phase PWM buck rectifier with input filter," *1991 VPEC Sem. Proc.*, 1991, pp. 229-237.
- 35. O. Ojo, and I. Bhat, "Analysis of three-phase PWM buck rectifier under modulation magnitude and angle control," *1993 IEEE IAS Annu. Meet. Conf. Rec.*, 1993, pp. 917-925.
- S. Hiti, V. Vlatkovic, D. Borojevic, F. C Lee, "A new control algorithm for three-phase PWM buck rectifier with input displacement factor compensation," *IEEE Trans. Power Electron.*, vol. 9, 1994, pp.173-180.