Advanced Electric Machine Theory (EE582000)

一、課程說明 (Course Description)

The purpose of this course is emphasized on the introduction to the static and dynamic characteristics of various electric machines. The theoretic backgrounds being established from this course will be helpful for performing the researches in the fields of motor drive, power system, microgrid and control engineering.

二、指定用書(Text Books)

- P. C. Krause, O. Wasynczuk and S. D. Sudhoff, *Analysis of Electric Machinery and Drive Systems*, 3rd edition, IEEE Press, 2013.
- Lecture notes.

三、參考書籍 (References)

Reference books:

- P. C. Krause and O. Wasynczuk, *Electromechanical Motion Devices*, McGraw-Hill, 1989.
- P. C. Krause, O. Wasynczuk and S. D. Sudhoff, *Analysis of Electric Machinery*, IEEE Press, 1995.
- P. C. Krause, O. Wasynczuk, and S. D. Sudhoff, *Analysis of Electric Machinery and Drive Systems*, 3rd ed., New York: Wiley-IEEE, 2013.
- P. C. Sen," *Principles of Electric Machines and Power Electronics*," 2nd Edition, 1996.
- Chee-Mun Ong, *Dynamic simulation of Electric Machinery using Matlab/Simulink*, Prentice Hall, 1998.
- Lyshevski, Sergey Edward, *Electromechanical Systems, Electric Machines and Applied Mechatronics*, CRC Press, 2000.
- D. W. Novotny and T. A. Lipo, 1996, *Vector Control and Dynamics of AC Drives*, Clarendon Press, New York.
- B. K. Bose, *Modern Power Electronics and AC Drives*, Prentice Hall, New Jersey, 2002
- R. Krishnan, *Electric Motor Drives Modeling, Analysis and Control*, Prentice Hall, New Jersey, 2001.
- John Chiasson, *Modeling and high-performance control of electric machines*, John Wiley & Sons, 2005.
- S. E. Lyshevski, *Nano- and Micro-Electromechanical Systems. Fundamentals of Nano- and Microengineering*, CRC Press, 2005.
- B. K. Bose, *Power Electronics and Motor Drives: Advances and Trends*, Academic Press, 2006.
- Seung-Ki Sul, *Control of Electric Machine Drive System*, IEEE Press, 2011.
- Chang-Ming Liaw, et. al., *Electromechanical Devices and Machines: Driving Control Technologies of New High-efficient Motors*, IntechOpen, October 2019.

四、教學方式 (Teaching Method)：非同步遠距教學 (Asynchronous distance instruction). (Use pre-recorded video)

五、教學進度 (Syllabus)

Month	Date	Content
Sep.	12	Introduction
	19	Ch1
	26	Ch1 & Ch3 HW#1
Oct.	3	Ch3 HW#2(Simulation)
	10	
	17	Ch4 HW#3
	24	Reviews
	31	Midterm test
Nov.	7	Ch5
	14	Oral Presentation
	21	Ch5
	28	Ch5
Dec.	5	Ch7 HW#4
	12	Ch12
	19	Reviews
	26	Final test
Jan.	2	
	9	Final project report

六、成績考核 (Evaluation):作業 (Exercises)、期中考 (Mid-term test)、期末考 (Final test)、模擬 (Simulation)、報告 (Report)。

七、可連結之網頁位址(Linked website)：http://www.ee.nthu.edu.tw/ycchang/

The topics covered in the textbook for different fields:

- ***Power engineers:*** *(Chapters 1,3,4,5,7,8,9,10),(11,13,14)*
  Basic principles for electric machine analysis: (1)
  Reference-frame theory (3)
  Symmetrical induction motors (4)
  Synchronous machines (5)
  Others: Machine equations in operational impedances and time constants (7), Linearized machine equations (8), Reduced-order machine equations (9), Symmetrical and unsymmetrical 2-phase induction machines (10).

- ***Motor drive specialists:*** ***(****All chapters).*

- ***Control specialists:*** *(Chapters 1,2,3,4,5,6,8,11,12,13,14,15)*
  Direct current machines (2)
  Linearized machine equations (8)
  Reduced-order machine equations (9)
  Semi-controlled bridge converters (AC/DC converters) (11)
  DC machine drives (AC/DC converter-fed and DC/DC converter-fed) (12)
  Fully controlled 3-phase bridge converters (DC/AC inverters) (13)
  Induction motor drives (14)
  Brushless DC motor drives (15)
- ***Power electronics engineers:*** Converters and motor drives *(Chapters 11 to 15)*.
- ***Power system (microgrid) engineers:*** *(Chapters 1 to 9, 11 to 15)*

Course contents:

1. Basic Principles for Electric Machine Analysis

◎ ***Electromechanical energy conversion:***

Derive the developed force or torque from energy or coenergy equation.

Coenergy:

Force equation: variables = current (*i*) and displacement (*x*):

$$f_{ek}(i_j, x_k) = \frac{\partial W_c(i_j, x_k)}{\partial x_k}$$

Torque equation: variables = current (*i*) and angular position (θ):

$$T_{ek}(i_j, \theta_k) = \frac{\partial W_c(i_j, \theta_k)}{\partial \theta_k}$$

Energy:

Force equation: variables = flux linkage (λ) and displacement (*x*):

$$f_{ek}(\lambda_j, x_k) = \frac{-\partial W_f(\lambda_j, x_k)}{\partial x_k}$$

Torque equation: variables = flux linkage (λ) and angular position (θ):

$$T_{ek}(\lambda_j, \theta_k) = \frac{-\partial W_f(\lambda_j, \theta_k)}{\partial \theta_k}$$

◎ *Winding inductances and voltage equations*

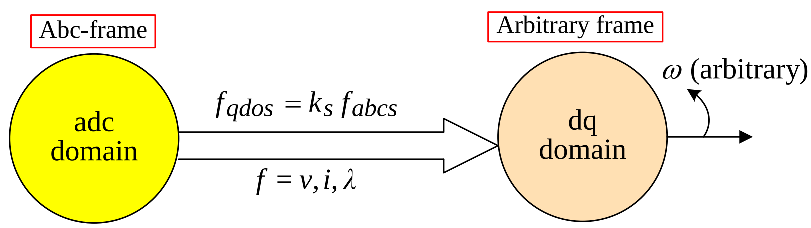
- ❖ Induction motor and synchronous machine.
- ❖ Some inductance components are functions of angular position, thus they are time-varying in nature.
- ❖ The voltage equations are multivariable, coupling, time-varying and nonlinear.

2. DC Machines

- ◎ *Dynamic characteristics:* Starting and step load change characteristics by simulations.
- ◎ *AC/DC Converters (Chapter 11)*
- ◎ *DC drives (AC/DC converter-fed and DC/DC converter-fed) (12)*
- ◎ *Linearized machine equations*
- ◎ *Speed control*

3. Reference-Frame Theory

- ◎ *General concept of reference frame transformation*
  (*Taking the synchronously rotating frame as an example, frame velocity* $\omega = \omega_e$)
- ◎ *Commonly used reference frames*
- ◎ *Transformation between reference frames*

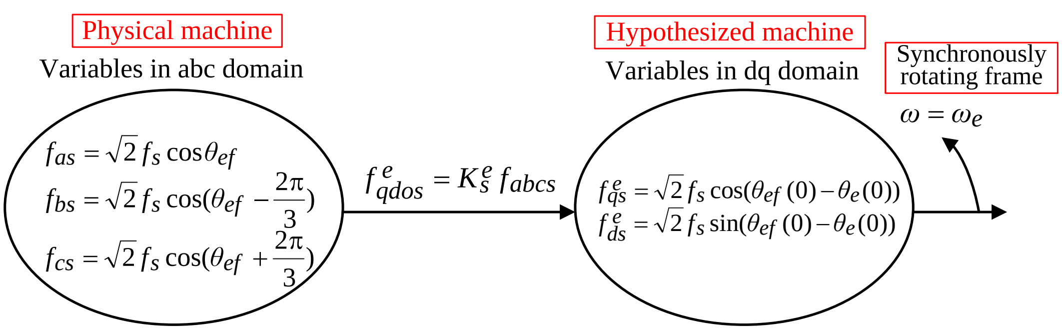


$$V_{abcs} = r_s i_{abcs} + \frac{d}{dt}\lambda_{abcs} = r_s i_{abcs} + \frac{d}{dt} L_s i_{abcs}$$

Time-varying

$$Vqdos = r_s i_{qdos} + \frac{d}{dt} l_{qdos} = r_s i_{qdos} + \frac{d}{dt}(k_s L_s (k_s)^{-1}) i_{qdos}$$

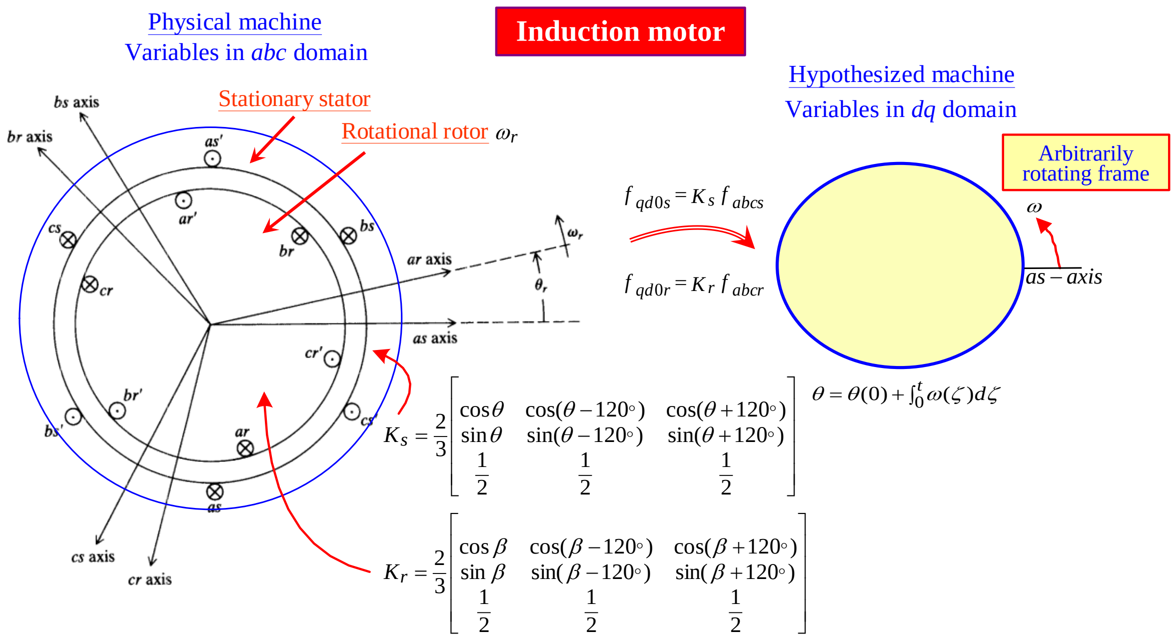
Time-invariant



$$\theta_{ef} = \int_0^t \omega_e(\zeta) d\zeta + \theta_{ef}(0) \qquad \theta_e = \int_0^t \omega_e(\zeta) d\zeta + \theta_{ef}(0)$$

<u>The advantages of reference frame transformation</u>

- The number of voltage equations is reduced
- The time-varying voltage equations becomes time-invariant ones
- Power-invariant transformation



4. Theory of Induction Machines

◎ *Voltage equations and torque equation (mechanical equation) in abc domain*

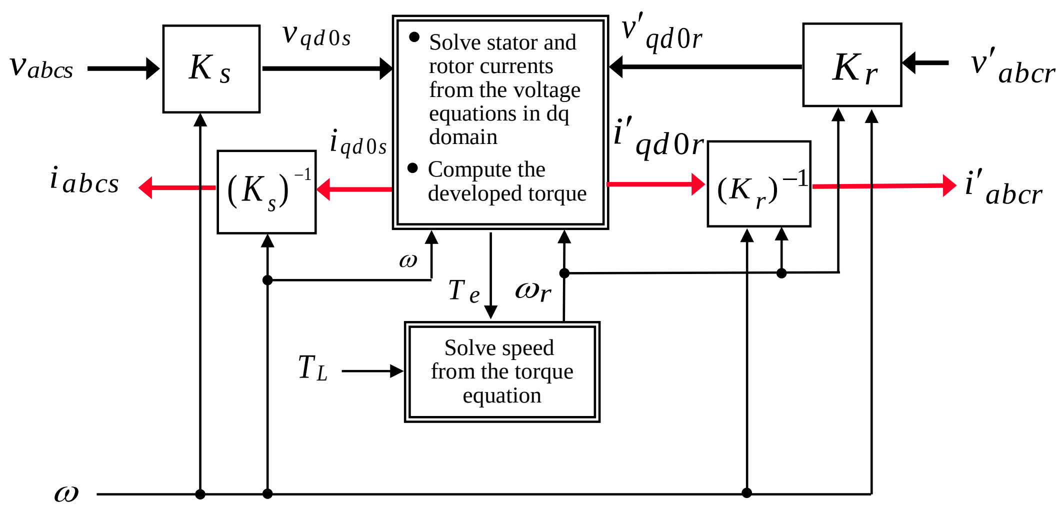
$$\begin{bmatrix} v_{abcs} \\ v_{abcr} \end{bmatrix} = \begin{bmatrix} r_s + pL_s & pL_{sr} \\ p(L_{sr})^T & r_s + pL_s \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix}$$

$$W_f = f(i_{abcs}, i_{abcr}), \quad T_e = g(i_{abcs}, i_{abcr})$$

$$T_e = J(\frac{2}{P})p\,\omega_r + B(\frac{2}{P})\,\omega_r + T_L$$

◎ *Voltage equations and torque equation (mechanical equation) in reference frame*

◎ *Static and dynamic characteristics by simulations*



The philosophy of computer simulation for induction motor in arbitrary reference frame

5. Theory of Synchronous Machines

- ◎ *Voltage equations and torque equation (mechanical equation) in abc domain*
- ◎ *Voltage equations and torque equation (mechanical equation) in reference frame (Park's equation): The stator voltage equations are transformed to the rotor, since rotor is already in dq domain.*
- ◎ *Static and dynamic characteristics by simulations*
- ◎ *Dynamic characteristics during faults by simulations*
- ◎ *Transient stability analysis*

6. Theory of Brushless DC Machines

- ◎ *Governing equations in abc-domain*
- ◎ *Governing equations in rotor reference frame*
- ◎ *State-state characteristics*
- ◎ *Dynamic performance*

7. Machine Equations in Operational Impedance and Time-Constants (of Synchronous Machines)

- ◎ *Derivation of equivalent circuit*
- ◎ *Time constants (transient and sub-transient) of synchronous machines*
- ◎ *Parameter estimation from short-circuit characteristics*
- ◎ *Parameter estimation from frequency response characteristics*

8. Linearized Machine Equations (of Induction Machines and Synchronous Machines)

- ◎ *Derivation of small-signal models using perturbation and linearization techniques*
- ◎ *Eigen-values*
- ◎ *Transfer functions*

9. Reduced-Order Machine Equations

- ◎ *Reduced-order equations of induction machine*
- ◎ *Reduced-order equations of synchronous machines*
- ◎ *Eigen-values*
- ◎ *Transfer function formulation*
- ◎ *Comparison between the full-order and reduced-order models*

10. Symmetrical and Unsymmetrical Two-Phase Induction Machines

11. Semiconductor Bridge Converters

12. DC Machine Drives

13. Fully Controlled Three-Phase Bridge Converters

14. Induction Motor Drives

15. Brushless DC Motor Drives

- ◎ *Permanent-magnet synchronous motor + inverter + rotor position sensing*
- ◎ *Mechanical commutation → electronic commutation*
- ◎ *Having torque generating capability like a DC shunt motor*
- ◎ *Two types of BDCM:*
  - ❖ *Speed drive:*

    Six-step inverter (square-wave BDCM).

    Using Hall-effect or photo sensor (discrete type).

❖ *Position servo drive:*

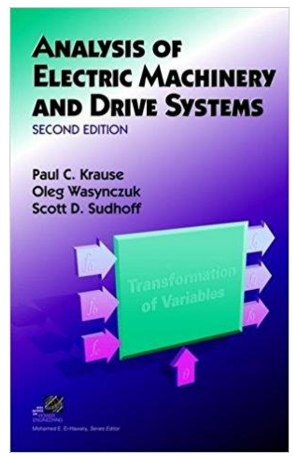
PWM inverter (sinusoidal BDCM).
Using absolute encoder, synchros or resolver rotor position sensor (continuous type).

16. Switched reluctance motors (Supplementary, Optional)

◎ Machine structure.
◎ The commonly used converters.
◎ Voltage and torque equations.
◎ Control approaches.
◎ Key issues for enhancing the driving performance of switched reluctance motor drive.

Appendix: Text book

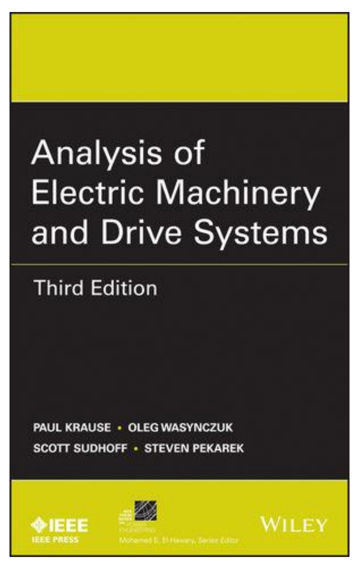
Analysis of Electric Machinery and Drive Systems, 2nd Edition, New York: Wiley-IEEE, 2002. Paul C. Krause, Oleg Wasynczuk, Scott D. Sudhoff



1. Basic Principles for Electric Machine Analysis.
2. Direct-Current Machines.
3. Reference-Frame Theory.
4. Symmetrical Induction Machines.
5. Synchronous Machines.
6. Theory of Brushless dc Machines.
7. Machine Equations in Operational Impedances and Time Constants.
8. Linearized Machine Equations.
9. Reduced-Order Machine Equations.
10. Symmetrical and Unsymmetrical 2-Phase Induction Machines.
11. Semicontrolled Bridge Converters.
12. DC Machine Drives.
13. Fully Controlled 3-Phase Bridge Converters.
14. Induction Motor Drives.
15. Brushless dc Motor Drives.

Appendix: Trigonometric Relations, Constants and Conversion Factors, and Abbreviations.

Analysis of Electric Machinery and Drive Systems, 3rd Edition
Paul C. Krause, Oleg Wasynczuk, Scott D. Sudhoff, Steven Pekarek
ISBN: 978-1-118-02429-4
680 pages, June 2013, Wiley-IEEE Press



Coverage includes:

- Completely new chapters on winding functions and machine design that add a significant dimension not found in any other text.
- A new formulation of machine equations for improving analysis and modeling of machines coupled to power electronic circuits
- Simplified techniques throughout, from the derivation of torque equations and synchronous machine analysis to the analysis of unbalanced operation
- A unique generalized approach to machine parameters identification

Other editions:

- P. C. Krause and O. Wasynczuk, *Electromechanical motion devices*, McGraw-Hill, 1989.
- P. C. Krause, O. Wasynczuk and S. D. Sudhoff, *Analysis of electric machinery*, IEEE Press, 1995.

  Chapter 9: Unbalanced operation of symmetrical induction machines.
  Chapter 10: Asynchronous and unbalanced operation of symmetrical synchronous machines.

- P. C. Krause, O. Wasynczuk, and S. D. Sudhoff, Analysis of electric machinery and drive systems, 3rd ed., New York: Wiley-IEEE, 2013.