Advanced Electric Machine Theory (EE582000)

(C. M. Liaw)

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 research in the fields of motor drive, power system 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, 2nd ed., New York: Wiley-IEEE, 2002. (Tentative).
- 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.

四、教學方式 (Teaching Method)：面授 (Oral).

五、教學進度 (Syllabus)

1. Fundamentals of electric machines

    1.1 Magnetically coupled circuits.

    1.2 Electromechanical energy conversion.

    1.3 Machine windings and air-gap MMF.

    1.4 Winding inductances and voltage equations.

2. DC machines: operating characteristics and dynamic modeling
    2.1 Voltage and torque equations.
    2.2 Types of DC machines.
    2.3 Dynamic characteristics.
    2.4 State equations, control system blocks.
3. Generalized reference-frame theory
    3.1 Transformation equations.
    3.2 Commonly used references reference frames.
    3.3 Transformation of a balanced set.
    3.4 Balanced steady-state voltage equations.
    3.5 Variables observed from various reference frames.
4. Symmetrical induction motors
    4.1 Voltage and torque equations in machine variables.
    4.2 Voltage and torque equations in reference frames.
    4.3 Per-unit system.
    4.4 Free-acceleration and dynamic load regulation.
    4.5 Computer simulation
5. Synchronous machines: basics
    5.1 Voltage and torque equations in machine variables.
    5.2 Voltage and torque equations in arbitrary reference frames.
    5.3 Voltage and torque equations in rotor reference frames.
    5.4 Per-unit system.
    5.5 Free-acceleration and dynamic load regulation.
    5.6 Computer simulation.
    5.7 Transient stability limit and critical clearing time of three-phase fault.
6. Synchronous machines: operational impedances
    6.1 Park's equations in operational form.
    6.2 Operational impedances.
    6.3 Standard machine reactances and time constants.
    6.4 Derived machine reactances and time constants.
    6.5 Parameters from frequency response characteristics.
7. Small signal modeling of induction and synchronous machines
    7.1 Linearization of machine equation.
    7.2 Eigen-value analysis.
    7.3 Transfer function models.
8. Reduced-order modeling for induction and synchronous machines
    8.1 Reduced-order equations.
    8.2 Large-excursion behavior predicted by Reduced-order equations.

8.3 Linearized reduced-order equations.
8.4 Eigenvalue analysis

9. Symmetrical and Unsymmetrical Two-Phase Induction Machines
   9.1 Symmetrical two-phase induction machines.
   9.2 Voltage and torque equations in machine variables for unsymmetrical two-phase induction machines.
   9.3 Voltage and torque equations in stationary reference frame for unsymmetrical two-phase induction machines.
   9.4 Single-phase induction machines.

10. DC Machine Drives
   10.1 Solid-state converters.
   10.2 AC-DC converter fed DC drives.
   10.3 One-quadrant DC-DC converter fed drive.
   10.4 Two-quadrant DC-DC converter fed drive.
   10.5 Four-quadrant DC-DC converter fed drive.

11. Induction Motor Drives
   11.1 V/f scalar control.
   11.2 Field-oriented control.
   11.3 Direct rotor field-oriented control.
   11.4 Indirect rotor field-oriented control.

12. Brushless DC Motor Drives
   12.1 Definition of brushless DC Motor.
   12.2 Square-wave brushless DC Motor.
   12.3 Sine-wave brushless DC Motor.
   12.4 Key issues for enhancing the driving performance of brushless DC Motor.

13. Switched reluctance motors
   13.1 Machine structure.
   13.2 The commonly used converters.
   13.3 Voltage and torque equations.
   13.4 Control approaches.
   13.5 Key issues for enhancing the driving performance of switched reluctance motor drive.

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

七、可連結之網頁位址(Linked website)：系建個人網址 (http://www.ee.nthu.edu.tw/cmliaw/).

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 engineers:*** *(Chapters 1 to 9)*

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.

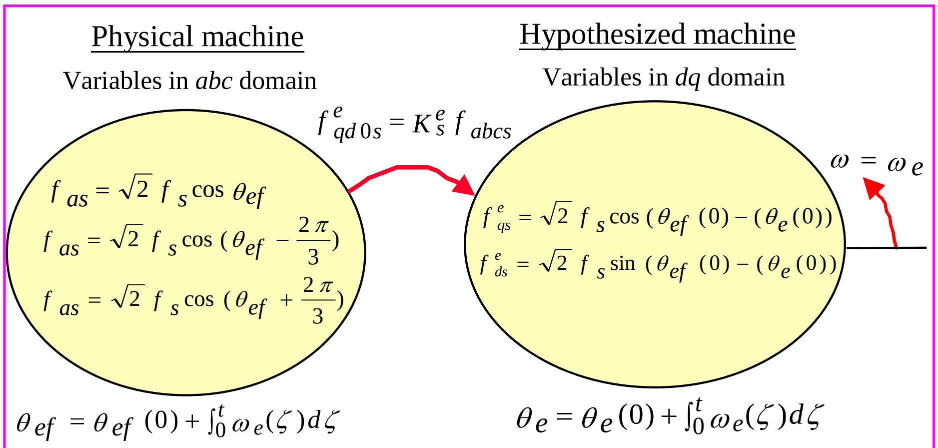
2. DC Machines

- ◎ *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* $\omega = \omega_e$)



<ins>The advantages of applying reference frame transformation</ins>

- The number of voltage equations is reduced, the developed power and torque expressions are simplified.
- The time-varying voltage equations become time-invariant ones.

- ◎ *Commonly used reference frames*
- ◎ *Transformation between reference frames*

4. Theory of Induction Machines

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

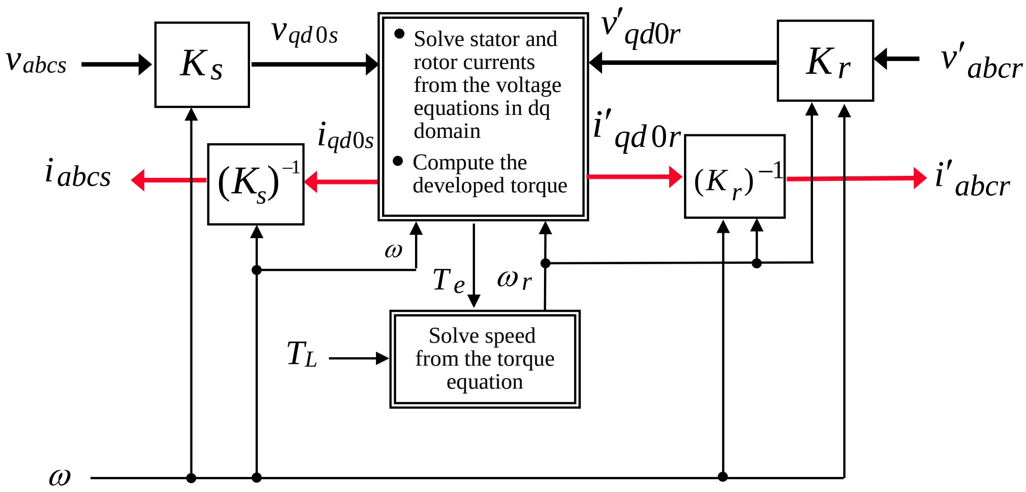
$$\begin{bmatrix} v_{abcs} \\ v_{abcr} \end{bmatrix} = \begin{bmatrix} r_s + pL_s & pL_{sr} \\ p(L_{sr})^T & r_s + pL_s \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix}$$

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

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

◎ *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).

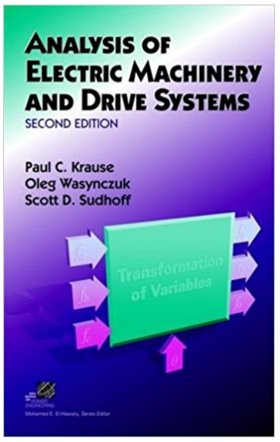
16. Switched reluctance motors (Supplementary)

- ◎ 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



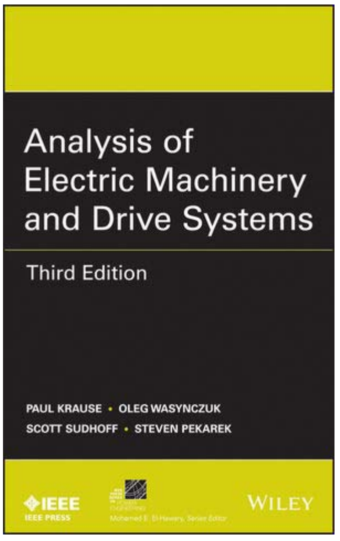
1. Basic Principles for Electric Machine Analysis.
2. Direct-Current Machines.
3. Reference-Frame Theory.
4. Symmetrical Induction Machines.
5. Synchronous Machines.
6. Theory of Brushless dc Machines.
7. Machine Equations in Operational Impedances and Time Constants.
8. Linearized Machine Equations.
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.