Advanced Electric Machine Theory (EE5820)
(C. M. Liaw)

Text book:

Reference books:

1. The topics covered in the textbook for different fields:

Power engineers: (Chapters 4,5,6,8,9,10,13)
  Induction motors: (4)
  Synchronous machines (5)
  Others: Operational impedances (6), reduced-order model (8), unbalanced operation (9,10), simulations (13).

Control specialists: (Chapters 2,7,11,13,14)
  Linearized models of AC machines: (7)
  Electric drives (2,13)
  2-phase induction servomotor (11)
  Brushless DC motor (14)
  Stepping motor (see reference book)
  Reduced-order model (8)

Power electronics engineers: (Chapters 2,13,14, Appendix B)
  Drives and converters.
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 \((\theta)\):

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

Energy:

Force equation: variables= flux linkage \((\lambda)\) and displacement \((x)\):

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

Torque equation: variables= current \((\lambda)\) and angular position \((\theta)\):

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

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.
3. Reference-Frame Theory

- General concept of reference frame transformation
  (Synchronously rotating frame as an example)

\[
\begin{align*}
\theta_{ef} &= \int_0^t \omega_\zeta(\zeta)d\zeta + \theta_{ef}(0) \\
\theta_e &= \int_0^t \omega_\zeta(\zeta)d\zeta + \theta_e(0)
\end{align*}
\]

The advantages of reference frame transformation
- The number of voltage equations is reduced
- 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
\[
\begin{bmatrix}
    v_{abcs} \\
    v'_{abcr}
\end{bmatrix} =
\begin{bmatrix}
    r_s + p L_s & p L'_{sr} \\
    p(L'_{sr})^T & r_r + p L_r
\end{bmatrix}
\begin{bmatrix}
    i_{abcs} \\
    i'_{abcr}
\end{bmatrix}
\]

\[
W_f = f(i_{abcs}, i'_{abcr}), \quad T_e = g(i_{abcs}, i'_{abcr})
\]

\[
T_e = J\left(\frac{2}{P}\right)p \omega_r + B\left(\frac{2}{P}\right)\omega_r + T_l
\]

- Voltage equations and torque equation (mechanical equation) in reference frame
- Static and dynamic characteristics by simulations

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. Operational Impedance and Time-Constants of Synchronous Machines

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

7. Linearized Equations of Induction Machines and Synchronous Machines

- Derivation of small-signal models using perturbation and linearization techniques
- Eigenvalues
- Transfer functions
8. Reduced-Order Equations

- Reduced-order equations of induction machine
- Reduced-order equations of synchronous machines
- Eigenvalues
- Transfer function formulation
- Comparison between the full-order and reduced-order models

9. Unbalanced Operation of Symmetrical Induction Machines

- What are balanced and symmetrical?
- Unbalanced stator voltages
- Unbalanced stator impedances
- Open-circuited stator phases
- Unbalanced rotor resistors
  (Unbalanced external rotor resistors added in a wound-rotor induction machine)

10. Asynchronous and Unbalanced Operation of Synchronous Machines

- Asynchronous operation:
  - Motor starting
  - Pole slipping

- Unbalanced operation:
  - Line-to-neutral fault
  - Line-to-line fault
  - Line-to-line-to-neutral fault

11. Symmetrical and Unsymmetrical Two-Phase Induction Machines

12. Computer Simulations of Induction and Synchronous Machines
The philosophy of computer simulation for induction motor in arbitrary reference frame

13. Reference Frame Theory Used in the Analysis and Simulations of Power Systems and Motor drives

14. Brushless DC Machines (BDCM):

- ☎️ 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).
Appendix: Text book

Analysis of Electric Machinery and Drive Systems, 2nd Edition
Paul C. Krause, Oleg Wasynczuk, Scott D. Sudhoff

Basic Principles for Electric Machine Analysis.
Direct-Current Machines.
Reference-Frame Theory.
Symmetrical Induction Machines.
Synchronous Machines.
Theory of Brushless dc Machines.
Machine Equations in Operational Impedances and Time Constants.
Linearized Machine Equations.
Reduced-Order Machine Equations.
Symmetrical and Unsymmetrical 2-Phase Induction Machines.
Semicontrolled Bridge Converters.
dc Machine Drives.
Fully Controlled 3-Phase Bridge Converters.
Induction Motor Drives.
Brushless dc Motor Drives.
Appendix: Trigonometric Relations, Constants and Conversion Factors, and Abbreviations.
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