EE 5200 - Lecture 1

Mon Aug 29, 2011

Topics for Today:

- Introductions - about 32 enrolled (maybe a few more adding)
  - ~14 students on campus
  - ~18 online students
- Startup
  - Web page: http://www.ee.mtu.edu/faculty/bamork/ee5200/
  - Book, references, syllabus, more are on web page.
  - Software - Matlab*, ASPEN, ATP/EMTP, spreadsheets
  - EE5200-L@mtu.edu (participation is 5% of your grade)
  - Lectures - new livestreams, archived video tutorials
  - Daily lecture notes scanned and .pdf file archived
  - Exercises posted as pdf on web page.
  - Grading: grad students must achieve B (80%) or higher
  - Grader: TBD <______@mtu.edu>

* On-line students: Ordering instructions sent via e-mail.
# EE 5200

**Advanced Methods in Power Systems Analysis**

Fall Semester 2011  
EERC B45 - M,W,F 1:05-1:55 pm  

**Dr. Bruce Mork | Office Hours**

**UPDATED WEEK-BY-WEEK**

- Course Syllabus  |  Pre-Req Material  |  Text & References  |  Useful Web Links  |  Homework Cover Sheet  |  Grades to Date  
- Term Project Guidelines  |  List of Term Projects  |  Past Term Project Examples: Ex:1  |  Ex:2  |  ATP Quick-Start  |  

Updated thru: Week 0 (under revision, updating for Fall’11)

Schedule and Coverage (Subject to Change Depending on Learning Needs of Students):

<table>
<thead>
<tr>
<th>Weekly Coverage (Read Material Before Class)</th>
<th>Lecture Date</th>
<th>Material Coverage:</th>
</tr>
</thead>
</table>
| 1 - Ch. 1  
Smart Grid Overview  
L1 - Aug 29th  
L2 - Aug 31st  
L3 - Sep 2nd  |  Lecture Date |  Lecture Date  |
| 2 - Ch. 1,2  
L5 - Sep 7th  
Sep 9th  |  Lecture Date |  Lecture Date  |

- **Course preperations:** Study course pre-req materials. Rate your skills. 
- Proper Use of "Closed" Voltage Phasor Diagrams for Graphical Analysis 
- Basic Phasor Analysis Concepts, Practice Problems, Intro to Matlab 
- Solutions: Ch.1 Review Probs (Complete by Sep 2nd)

**Labor Day, no lecture:**  
CKTS - Due Sep 10th, 5pm Mag Circuits Review 
Suggested Study Probs: 2.2, 2.4, 2.6, 2.8, 2.9, 2.14, 2.16, 2.17, 2.18, 2.21 (Ch.2 Soln) 
Transformer connections (Delta, Y, auto, zig-zag), core structure (G&S Overview) 
IEEE/IEC Phase Shifts (std 30°, non-std), 3-Winding Transformers, Nameplate, Schematic 
K-Day, no lecture.  
XFMR Homework (Due 5pm Fri Sep 17th)
EE5200

- Review
- Notations
- Technical English
- Adjust to grad school.
- Software
  - Spreadsheets
  - Matlab
  - Aspen - LF, Sc, Relay
  - ATP/EMTP
  - WebCT
Graduate School

- Class size, proactive, anticipate.
- Size of exercises, scope, lead time.
- Concept-based approaches.
- Creative thought process.
- Communications.
  - E-mail
  - Spoken / informal / phone
  - Presentations / "ppt."
  - Written reports.

- Research & Development ( & Design)
  - "Scientific Method", conceptually sound.
Grad School – What to Expect

- Smaller size classes. Everybody is a top student, high expectations. Top students to study with, collaborate with.
- Take an active role in your education. Anticipate what needs to be done. Ask questions during lecture.
- Open-ended problems and projects, larger scope, longer deadlines.
- Professor will create an environment (lecture, lab, research) for you to succeed in, you do the rest.
- Stress concept-based approaches (instead of procedural), abstract thinking, reward for developing creative innovative approaches.
- Communications – develop excellent speaking and writing skills.
- Research – scientific method, conceptually sound, make an advancement on existing state of the art.
TIME MANAGEMENT

• Plan on 10 hrs/wk of focused productive time.
• Grad courses draw on pre-req concepts from undergraduate courses, so some weeks may be more.
• Online students:
  • View lectures at time convenient to work schedule.
  • Must keep to the same week-by-week schedule as on-campus students.
• Online students may have field assignments or need to travel. We try to be flexible...
• Homeworks:
  • Look it over early on, start discussions on e-mail forum
  • Take advantage of e-mail discussions: combine practical knowledge of online students with applied math and theoretical knowledge of on-campus folks.
  • Grad courses – can’t wait ‘til the night before to get started, or there is no way you can complete it.
On-Campus
Theory, Math

On-line
Practice

Faculty

5%

Use the e-mail Forum
EES200-L@mtu.edu!
• REVIEW, remedial: - Circuit Analysis Basics (Pre-Req Lect. #1)
  • Do all exercises in Ch.1 (solutions are posted)
  • Active vs. passive sign convention
  • Dual-subscript notation, single-subscript (implied reference)
  • Closure of subscripts in mesh equation
  • Euler’s Identity - basis for phasor analysis! See handout.
  • Drawing phasor diagrams, arrowheads
  • Three-phase, “open” vs. “closed” voltage phasor diagrams
  • Errata in text book - Figs. 1.16, 1.17.

• Study Chapters 1 and 2, view archive lectures 1-4
• No class on Friday Sep 11th (K-Day recess in afternoon)
• Classes resume on Monday.
• Note - I will be away on
  • Mon Sep 28th - Personal Travel (video lecture)
  • Nov 4th thru 6th - Minnesota Power Systems Conference
• Need schedules of on-campus students to set weekly timeslot for videotaping make-up lectures.
Prerequisite Material, Useful References (see course web page)

- Euler's Identity - The foundation of phasor analysis, as well as hyperbolic functions (used for long transmission lines)
- Basic Circuit Analysis, Thevenizing, Phasor Analysis, Impedance, P,Q,S, etc.: EE3120 pre-req practice problems | Solutions
- Basic 3-Phase Phasor Analysis - Review problem from EE3120
- Magnetic Circuits - quick review and introduction of how a transformer works
- Mutual Inductance - concept handout from EE3120 (refer to Section 2.2 of your text)
- Transformers 101 - Everything you wanted (or suddenly need to know) about transformers but were afraid to ask...
- Delta-Wye Transformer - detailed example with solution from EE3120
- EE 4221 Pre-Req Course Description
- EE 4222 Pre-Req Course Description
- Pre-Req Review Videos with Notes (from 2003 Archives)
  - Basic Circuit Analysis, Phasors, Three Phase Phasors: Lect 1 (skip first 12 mins) | Lect 1 Notes
  - Phasor Diagrams, Ideal Transformers, Nodal Analysis: Lect 2 (skip first 6:20) | Lect 2 Notes
  - Nodal Analysis, 3-phase circuits, Deltas and Wyes, Per Unit System: Lect 3 (skip first 3 mins) | Lect 3 Notes
  - Active & Passive Sign Convention for power flow, Per Unit, Transformers, Symmetrical Components: Lect 4 (skip first 2 mins) | Lect 4 Notes
  - Transformers, Induced Voltage & Polarity Marks, Phase Shift: Lect 5 (skip 3:45 - 5:20) | Lect 5 Notes
  - Phase Shift in Transformers, Phasor Diagrams, Application of Symmetrical Components: Lect 6 (skip first 3 mins) | Lect 6 Notes
  - Sample .m files from above tutorials: | for_ex.m | r2p.m | for_if_ex.m | while_ex.m | ft.m |
Notations:

The voltages and currents we are dealing with are RMS phasor values. In the equations we develop, it is necessary to refer to their magnitudes and angles. For example, the voltage at bus $k$ with respect to reference is:

RMS phasor value: $\tilde{V}_k$ or $V_k$ or $\frac{V_k}{\delta_k}$

RMS magnitude: $|\tilde{V}_k|$ or just $V_k$  
Angle of $\tilde{V}_k$: $\delta_k$

We also need to refer to individual elements of $[Y_{BUS}]$. The entry in the $i,j$ position is a complex number $\tilde{y}_{ij}$ with a magnitude of $y_{ij}$ and an angle of $\theta_{ij}$.

$$Y_{BUS} = \begin{bmatrix} \ddots & \ddots & \ddots \\ \ddots & \ddots & \ddots \\ \ddots & \ddots & \ddots \end{bmatrix}$$
Contents
3 The Synchronous Machine 87
 3.1 Description of the Synchronous Machine 88
 3.2 Three-Phase Generation 91
 3.3 Synchronous Reactance and Equivalent Circuits 100
 3.4 Real and Reactive Power Control 105
 3.5 Loading Capability Diagram 110
 3.6 The Two-Axis Machine Model 117
 3.7 Voltage Equations: Salient-Pole Machine 123
 3.8 Transient and Subtransient Effects 127
 3.9 Short-Circuit Currents 132
 3.10 Summary 136
 3.11 Problems 136

4 Series Impedance of Transmission Lines 141
 4.1 Types of Conductors 142
 4.2 Resistance 143
 4.3 Tabulated Resistance Values 146
 4.4 Inductance of a Conductor Due to Internal Flux 146
 4.5 Flux Linkages between Two Points External to an Isolated Conductor 149
 4.6 Inductance of a Single-Phase Two-Wire Line 151
 4.7 Flux Linkages of One Conductor in a Group 153
 4.8 Inductance of Composite-Conductor Lines 155
 4.9 The Use of Tables 159
 4.10 Inductance of Three-Phase Lines with Equilateral Spacing 161
 4.11 Inductance of Three-Phase Lines with Unsymmetrical Spacing 164
 4.12 Inductance Calculations for Bundled Conductors 165
 4.13 Summary 167

5 Capacitance of Transmission Lines 170
 5.1 Electric Field of a Long, Straight Conductor 171
 5.2 The Potential Difference between Two Points Due to a Charge 172
 5.3 Capacitance of a Two-Wire Line 173
 5.4 Capacitance of a Three-Phase Line with Equilateral Spacing 177
 5.5 Capacitance of a Three-Phase Line with Unsymmetrical Spacing 180
 5.6 Effect of Earth on the Capacitance of Three-Phase Transmission Lines 183
 5.7 Capacitance Calculations for Bundled Conductors 186
 5.8 Parallel-Circuit Three-Phase Lines 188
 5.9 Summary 190
 5.10 Problems 191

6 Current and Voltage Relations on a Transmission Line 193
 6.1 Representation of Lines 195
 6.2 The Short Transmission Line 196

7 The Admittance Model and Network Calculations 233
 7.1 Branch and Node Admittances 239
 7.2 Mutually Coupled Branches in \( y_{\text{bus}} \) 245
 7.3 An Equivalent Admittance Network 251
 7.4 Modification of \( y_{\text{bus}} \) 255
 7.5 The Network Incidence Matrix and \( y_{\text{bus}} \) 257
 7.6 The Method of Successive Elimination 263
 7.7 Node Elimination (Kraus Reduction) 271
 7.8 Triangular Factorization 274
 7.9 Sparsity and Near-Optimal Ordering 279
 7.10 Summary 280
 7.11 Problems 280

8 The Impedance Model and Network Calculations 283
 8.1 The Bus Admittance and Impedance Matrices 284
 8.2 Thevenin's Theorem and \( z_{\text{bus}} \) 287
 8.3 Modification of an Existing \( z_{\text{bus}} \) 294
 8.4 Direct Determination of \( z_{\text{bus}} \) 301
 8.5 Calculation of \( z_{\text{bus}} \) Elements from \( y_{\text{bus}} \) 306
 8.6 Power Invariant Transformations 310
 8.7 Mutually Coupled Branches in \( z_{\text{bus}} \) 316
 8.8 Summary 324
 8.9 Problems 324

9 Power-Flow Solutions 329
 9.1 The Power-Flow Problem 329
 9.2 The Gauss-Seidel Method 333
 9.3 The Newton-Raphson Method 342
 9.4 The Newton-Raphson Power-Flow Solution 347
 9.5 Power-Flow Studies in System Design and Operation 355
 9.6 Regulating Transformers 361
9.7 The Decoupled Power-Flow Method 368
9.8 Summary 374
Problems 376

10 Symmetrical Faults 380
10.1 Transients in Rf Series Circuits 381
10.2 Internal Voltages of Loaded Machines under Fault Conditions 383
10.3 Fault Calculations Using \( Z_{th} \) Equivalent Circuits 390
10.4 Fault Calculations Using \( Z_{eq} \) Equivalent Circuits 395
10.5 The Selection of Circuit Breakers 402
10.6 Summary 411
Problems 412

11 Symmetrical Components and Sequence Networks 416
11.1 Synthesis of Unsymmetrical Phasors from Their Symmetrical Components 417
11.2 The Symmetrical Components of Unsymmetrical Phasors 418
11.3 Symmetrical Y and \( \Delta \) Circuits 422
11.4 Power in Terms of Symmetrical Components 427
11.5 Sequence Circuits of Y and \( \Delta \) Impedances 429
11.6 Sequence Circuits of a Symmetrical Transmission Line 435
11.7 Sequence Circuits of the Synchronous Machine 442
11.8 Sequence Circuits of Y-\( \Delta \) Transformers 449
11.9 Unsymmetrical Series Impedances 459
11.10 Sequence Networks 461
11.11 Summary 467
Problems 467

12 Unsymmetrical Faults 470
12.1 Unsymmetrical Faults on Power Systems 470
12.2 Single Line-to-Ground Faults 482
12.3 Line-to-Line Faults 494
12.4 Double Line-to-Ground Faults 500
12.5 Demonstration Problems 512
12.6 Open-Conductor Faults 523
12.7 Summary 527
Problems 527

13 Economic Operation of Power Systems 531
13.1 Distribution of Load between Units within a Plant 532
13.2 Distribution of Load between Plants 540
13.3 The Transmission-Loss Equation 543
13.4 An Interpretation of Transformation C 552
13.5 Classical Economic Dispatch with Losses 555
13.6 Automatic Generation Control 562
13.7 Unit Commitment 572

14 Zth Methods in Contingency Analysis 578
14.1 Adding and Removing Multiple Lines 591
14.2 Piecewise Solution of Interconnected Systems 592
14.3 Analysis of Single Contingencies 601
14.4 Analysis of Multiple Contingencies 611
14.5 Contingency Analysis by dc Model 620
14.6 System Reduction for Contingency and Fault Studies 628
14.7 Summary 636
Problems 636

15 State Estimation of Power Systems 641
15.1 The Method of Least Squares 642
15.2 Statistics, Errors, and Estimates 650
15.3 Test for Bad Data 653
15.4 Power System State Estimation 664
15.5 The Structure and Formation of \( H_e \) 677
15.6 Summary 687
Problems 688

16 Power System Stability 695
16.1 The Stability Problem 695
16.2 Rotor Dynamics and the Swing Equation 698
16.3 Further Considerations of the Swing Equation 702
16.4 The Power-Angle Equation 707
16.5 Synchronizing Power Coefficients 714
16.6 Equal-Area Criterion of Stability 717
16.7 Further Applications of the Equal-Area Criterion 724
16.8 Multimachine Stability Studies: Classical Representation 727
16.9 Step-by-Step Solution of the Swing Curve 734
16.10 Computer Programs for Transient Stability Studies 741
16.11 Factors Affecting Transient Stability 743
16.12 Summary 745
Problems 746

Appendix A 748
A.1 Distributed Windings of the Synchronous Machine 754
A.2 P-Transformation of Stator Quantities 763

Appendix B 766
B.1 Sparsity and Near-Optimal Ordering 766
B.2 Sparsity of the Jacobian 771

Index 777