Topics for Today:

• Announcements
  • Software: Matlab? Will begin using as early as next week.
  • Office hrs: 2pm, M,W,F (will try this, can adjust if needed)
  • Grader Office Hrs: 2-4pm EERC 123 (learning center)
  • Office: EERC 614. Phone: 906.487.2857
  • Ch.2 Solutions posted on web page, go thru them for review.
  • XFMR exercises will be posted, due Sep 18th 9am ET.

• Chapter 2 - Review: Transformers and circuits w/transformers
  • Single phase transformers
  • Basic structure: winding R and Leakage, Core losses and saturation
  • 3-phase transformer banks and phase shifts (ANSI/IEEE vs. IEC)
  • Standard 30° shift transformers, non-standard connections
  • Pos/neg sequence phase shifts
  • Autotransformers
  • Load Tap Changing (LTC) transformers

• Comments on sequence networks

1. Core (no-load) losses minimized by utilizing laser-scribed, super-grain-oriented steel.
2. Lamination width customized to achieve a near perfect-circle core cross section, resulting in the efficient use of materials plus a lighter, more compact, high performance transformer.
3. Coil assembly rigidly braced in a high-strength frame that distributes clamping forces around the full circumference of the windings.
4. Submerged-arc welding process produces deep penetration welds, virtually eliminating leakage from welded tank joints.
5. Inside tank surfaces are painted white to facilitate internal inspection.
6. Transformer exterior coated to a minimum thickness of 3 mils; this coating has superior endurance characteristics and meets the ANSI C57.12.28 standard.
7. Galvanized radiators provide excellent corrosion resistance and require minimal maintenance (fan guards and blades also galvanized).
8. Material-stabilized coils are pressure-fit within the core frame.
9. Patented DETC (De-Energized Tap Changer) features simple and compact in-line contact arrangement (Patent Number: 5,744,764)
10. Waukesha® Type UZD Load Tap Changer designed to withstand up to a half-million operations without the need for contact replacement.
11. Worldbox® Control Enclosure features IEC standard components and is easy to maintain and service in the field.
Loadflow - Phasor
S.C. - 
Stability - Both Phasor (Grid Calcs) and time (machine dynamics)

$0, \Delta t, 2\Delta t, \ldots$

Lightning - time (impulse)
Switching - time (step)

Insulation Design -
CONTENTS

EE 5200 TEXT

Preface xvii

1 Basic Concepts
1.1 Introduction 1
1.2 Single-Subscript Notation 1
1.3 Double-Subscript Notation 4
1.4 Power in Single-Phase AC Circuits 5
1.5 Complex Power 10
1.6 The Power Triangle 10
1.7 Direction of Power Flow 11
1.8 Voltage and Current in Balanced Three-Phase Circuits 14
1.9 Power in Balanced Three-Phase Circuits 24
1.10 Per-Unit Quantities 25
1.11 Changing the Base of Per-Unit Quantities 29
1.12 Node Equations 30
1.13 The Single-Line or One-Line Diagram 34
1.14 Impedance and Reactance Diagrams 36
1.15 Summary 37
Problems 37

2 Transformers
2.1 The Ideal Transformer 41
2.2 Magnetically Coupled Coils 41
2.3 The Equivalent Circuit of a Single-Phase Transformer 46
2.4 Per-Unit Impedances in Single-Phase Transformer Circuits 51
2.5 Three-Phase Transformers 56
2.6 Three-Phase Transformers: Phase Shift and Equivalent Circuits 59
2.7 The Autotransformer 64
2.8 Per-Unit Impedances of Three-Winding Transformers 71
2.9 Tap-Changing and Regulating Transformers 72
2.10 The Advantages of Per-Unit Computations 76
2.11 Summary 80
Problems 82

xi
3 The Synchronous Machine
3.1 Description of the Synchronous Machine
3.2 Three-Phase Generation
3.3 Synchronous Reactance and Equivalent Circuits
3.4 Real and Reactive Power Control
3.5 Loading Capability Diagram
3.6 The Two-Axis Machine Model
3.7 Voltage Equations: Salient-Pole Machine
3.8 Transient and Subtransient Effects
3.9 Short-Circuit Currents
3.10 Summary

4 Series Impedance of Transmission Lines
4.1 Types of Conductors
4.2 Resistance
4.3 Tabulated Resistance Values
4.4 Inductance of a Conductor Due to Internal Flux
4.5 Flux Linkages between Two Points External to an Isolated Conductor
4.6 Inductance of a Single-Phase Two-Wire Line
4.7 Flux Linkages of One Conductor in a Group
4.8 Inductance of Composite-Conductor Lines
4.9 The Use of Tables
4.10 Inductance of Three-Phase Lines with Equilateral Spacing
4.11 Inductance of Three-Phase Lines with Unequal Spacings
4.12 Inductance Calculations for Bundled Conductors
4.13 Summary

5 Capacitance of Transmission Lines
5.1 Electric Field of a Long, Straight Conductor
5.2 The Potential Difference between Two Points Due to a Charge on a Conductor
5.3 Capacitance of Two-Wire Line
5.4 Capacitance of a Three-Phase Line with Equilateral Spacing
5.5 Capacitance of a Three-Phase Line with Unequal Spacings
5.6 Effect of Earth on the Capacitance of Three-Phase Transmission Lines
5.7 Capacitance Calculations for Bundled Conductors
5.8 Parallel-Circuit Three-Phase Lines
5.9 Summary

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

7 The Admittance Model and Network Calculations
7.1 Branch and Node Admittances
7.2 Mutually Coupled Branches in \( Y_{\text{m}} \)
7.3 An Equivalent Admittance Network
7.4 Modification of \( Y_{\text{m}} \)
7.5 The Network Incidence Matrix and \( Y_{\text{m}} \)
7.6 The Method of Successive Elimination
7.7 Node Elimination (Kruskal Reduction)
7.8 Triangular Factorization
7.9 Sparsity and Near-Optimal Ordering
7.10 Summary

8 The Impedance Model and Network Calculations
8.1 The Bus Admittance and Impedance Matrices
8.2 Thévenin's Theorem and \( Z_{\text{m}} \)
8.3 Modification of an Existing \( Z_{\text{m}} \)
8.4 Direct Determination of \( Z_{\text{m}} \)
8.5 Calculation of \( Z_{\text{m}} \) Elements from \( Y_{\text{m}} \)
8.6 Power Invariant Transformations
8.7 Mutually Coupled Branches in \( Z_{\text{m}} \)
8.8 Summary

9 Power-Flow Solutions
9.1 The Power-Flow Problem
9.2 The Gauss-Seidel Method
9.3 The Newton-Raphson Method
9.4 The Newton-Raphson Power-Flow Solution
9.5 Power-Flow Studies in System Design and Operation
9.6 Regulating Transformers
10 Symmetrical Faults
10.1 Transients in Rf. Series Circuits 380
10.2 Internal Voltages of Loaded Machines under Fault Conditions 381
10.3 Fault Calculations Using Z_{sub} 382
10.4 Fault Calculations Using Z_{sub} Equivalent Circuits 383
10.5 The Selection of Circuit Breakers 384
10.6 Summary 385
10.7 Problems 386

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 Δ Circuits 419
11.4 Power in Terms of Symmetrical Components 420
11.5 Sequence Circuits of Y and Δ Impedances 421
11.6 Sequence Circuits of a Symmetrical Transmission Line 422
11.7 Sequence Circuits of the Synchronous Machine 423
11.8 Sequence Circuits of Y-Δ Transformers 424
11.9 Unsymmetrical Series Impedances 425
11.10 Sequence Networks 426
11.11 Summary 427
11.12 Problems 428

12 Unsymmetrical Faults 470
12.1 Unsymmetrical Faults on Power Systems 471
12.2 Single Line-to-Ground Faults 472
12.3 Line-to-Line Faults 473
12.4 Double Line-to-Ground Faults 474
12.5 Demonstration Problems 475
12.6 Open-End Faults 476
12.7 Summary 477
12.8 Problems 478

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 533
13.3 The Transmission-Loss Equation 534
13.4 An Interpretation of Transformation C 535
13.5 Classical Economic Dispatch with Losses 536
13.6 Automatic Generation Control 537
13.7 Unit Commitment 538

14 Z_{sub} Methods in Contingency Analysis 590
14.1 Adding and Removing Multiple Lines 591
14.2 Piecewise Solution of Interconnected Systems 592
14.3 Analysis of Single Contingencies 593
14.4 Analysis of Multiple Contingencies 594
14.5 Contingency Analysis by Δ Model 595
14.6 System Reduction for Contingency and Fault Studies 596
14.7 Summary 597
14.8 Problems 598

15 State Estimation of Power Systems 641
15.1 The Method of Least Squares 642
15.2 Statistics, Errors, and Estimates 643
15.3 Test for Bad Data 644
15.4 Power System State Estimation 645
15.5 The Structure and Formation of H_{sub} 646
15.6 Summary 647
15.7 Problems 648

16 Power System Stability 695
16.1 The Stability Problem 696
16.2 Rotor Dynamics and the Swing Equation 697
16.3 Further Considerations of the Swing Equation 698
16.4 The Power-Angle Equation 699
16.5 Synchronizing Power Coefficients 700
16.6 Equal-Area Criterion of Stability 701
16.7 Further Applications of the Equal-Area Criterion 702
16.8 Load-Machine Stability Studies: Classical Representation 703
16.9 Step-by-Step Solution of the Swing Curve 704
16.10 Computer Programs for Transient Stability Studies 705
16.11 Factors Affecting Transient Stability 706
16.12 Summary 707
16.13 Problems 708

Appendix A 748
A.1 Distributed Windings of the Synchronous Machine 749
A.2 F-Transformation of Stator Quantities 750

Appendix B 766
B.1 Sparsity and Near-Optimal Ordering 767
B.2 Sparsity of the Jacobian 768

Index 777
1) [15pts] For the following circuit, \( v_1(t) = 100 \cos(\omega t + 0^\circ) \), \( v_2(t) = 120 \sin(\omega t - 30^\circ) \) and \( Z_{12} = 0.5 - j0.5 \Omega \).

a) Convert \( v_1(t) \) and \( v_2(t) \) to their phasor equivalents \( V_1 \) and \( V_2 \).

b) Calculate \( I_{12} \).

c) Calculate the complex power \( S \) consumed by "source 2".

d) In terms of generator or load, what are sources 1 & 2? Was the correct guess made in labeling current direction?

e) What is the power factor of "source 1"?

- Phasor Analysis
- \( \vec{V}, \vec{I}, \) subscripts
- Polarity
- Flow direction of \( P, Q \)
Time Domain - Simulation
- ATP
- Matlab

\[ \Delta t = \text{uniform timestep} \]

real no.

\[ +1 \]

\[ -1 \]

\[ \pm \Delta t \]

time series
Power

Matlab

\[ P = V \times I \]

\[ P_{AVG} = \frac{1}{T} \int P(t) \, dt \]

\[ PF = 1 \]

\[ R \]

\[ P(t) = V(t) \times I(t) \]

\[ PF = 0 \]

\[ P_{AVG} = 0 \]
Waukesha Quality Inside
Means Reliability Is On Your Side

Load Tap Changer is designed to withstand up to a half-million operations without need for contact replacement.

Lamination width customized to achieve a near perfect-circle core cross section, resulting in the most efficient use of materials plus a lighter, more compact high-performance transformer.

Low no-load losses result from use of laser-scribed, super-grain-oriented steel.

Transformer exterior is coated to a minimum thickness of 3 mils. This coating has superior endurance characteristics and meets the ANSI C57.12.28 standard.

Material-stabilized coils are pressure-fit within the core frame.

Galvanized radiators provide excellent corrosion resistance and minimal maintenance.

De-energized tap changer features simple and compact in-line contact arrangement.

Coil assembly is rigidly braced in a high-strength frame that distributes clamping forces around the full circumference of the windings.

Submerged-arc process produces deep weld penetration, virtually eliminating leakage from welded tank joints.

Inside tank surfaces are painted white to facilitate internal inspection.

Waukesha Electric Systems offers component parts for transformer upgrades and repair, as well as extensive field service support that includes transformer moving, hauling and rigging, vacuum filling and oil processing, inspection, testing and customer training.

Waukesha Electric Systems
World Headquarters:
400 S. Prairie Avenue
Waukesha, WI 53186-5940
800.835.2732

U.S. Manufacturing:
Waukesha, WI 800.835.2732
Goldsboro, NC 800.758.4384

Service, Parts, Training:
High Voltage Supply
Dallas, TX 800.338.5526

energy solutions...to power your future

1. Core (no-load) losses minimized by utilizing laser-scribed, super-grain-oriented steel.
2. Lamination width customized to achieve a near perfect-circle core cross section, resulting in the efficient use of materials plus a lighter, more compact, high performance transformer.
3. Coil assembly rigidly braced in a high-strength frame that distributes clamping forces around the full circumference of the windings.
4. Submerged-arc welding process produces deep penetration welds, virtually eliminating leakage from welded tank joints.
5. Inside tank surfaces are painted white to facilitate internal inspection.
6. Transformer exterior coated to a minimum thickness of 3 mils; this coating has superior endurance characteristics and meets the ANSI C57.12.28 standard.
7. Galvanized radiators provide excellent corrosion resistance and require minimal maintenance (fan guards and blades also galvanized).
8. Material-stabilized coils are pressure-fit within the core frame.
9. Patented DETC (De-Energized Tap Changer) features simple and compact in-line contact arrangement (Patent Number: 5,744,764)
10. Waukesha® Type UZD Load Tap Changer designed to withstand up to a half-million operations without the need for contact replacement.
11. Worldbox® Control Enclosure features IEC standard components and is easy to maintain and service in the field.
Cooling
- Oil
- Heat exch.
- Pumps, fans

Monitoring
- Temp: oil, coils gases

Coil Design
- insulation
  - higher V
  - coil-coil, coil-phase
  - Bil, Bsk

- LTCs (off-nominal turns ratio)
- ±5% ±10%
How many possibilities are there for Δ-Y or Y-Δ phase shifts?

\[\begin{align*}
\pm 30^\circ \\
\pm 90^\circ \\
\pm 150^\circ \\
\end{align*}\]

6 each \[\Rightarrow 12 \text{ total.}\]

Auto- Δ
Zig-Zig
Extended Δ.
Three-Phase Transformers

All of these can and are used to indicate the same winding connections:

IEEE Stds:

Schematic

Circuit 3-line diagram

In Europe and much of the world:

IEC Stds: Dyn11

One-Line:
\[
\Delta \triangleleft \frac{x_3}{x_2} \times x_1
\]

0° phase shift.

Zig-Zag

H2

H1
Balanced 3-ph voltages:
\[ |\tilde{V}_{AG}| = |\tilde{V}_{BG}| = |\tilde{V}_{CG}| \]
Extend Delta
Transformer Phase Shifts

- See Δ-Y transformer nameplate

pos seg voltage "phase shift"
3-PHASE XFMR BANK

Ex: Δ-Y (Oyn1)

From: Review Lecture 6
SEQUENCE NETWORKS FOR TRANSFORMERS
\[ I_{N} = 3I_{A0} G \]

\[ V_{DROP} = 3I_{A0} Z_{N} = V_{NG} \]
triplen harmonics
buried tertiary
buried delta

delta:
- trap tripplen harmonics
- zero seq circ path
- Aux power (station service)
- Protection
  - CTs
\[ V_{A1} = V_{O1} \left(1/30^\circ\right) \]

PRI POS SEQ VOLTAGES

SEC POS SEQ VOLTAGES

PRI POS SEQ CURRENTS

SEC POS SEQ CURRENTS

\[ V_{A2} = V_{O2} \left(1/-30^\circ\right) \]

PRI NEG SEQ VOLTAGES

SEC NEG SEQ VOLTAGES

PRI NEG SEQ CURRENTS

SEC NEG SEQ CURRENTS

ANSI STANDARD 30-DEGREE SHIFT WYE-DELTA
\[ V_{A1} = V_{a1} \left(1/30^\circ\right) \]

**PRI POS SEQ VOLTAGES**

\[ I_{A1} = I_{AB1} - I_{CA1} \]

**PRI POS SEQ CURRENTS**

\[ V_{A2} = V_{a2} \left(1/-30^\circ\right) \]

**PRI NEG SEQ VOLTAGES**

\[ I_{A2} = I_{AB2} - I_{CA2} \]

**PRI NEG SEQ CURRENTS**

\[ I_{c2} \]

**SEC NEG SEQ CURRENTS**

\[ I_{a2} \]

\[ I_{b2} \]

\[ I_{c2} \]

**SEC NEG SEQ VOLTAGES**

**ANSI STANDARD 30-DEGREE SHIFT DELTA-WYE**