# ECE 325 – Electric Energy System Components 1 - Introduction to power systems



Instructor: Kai Sun Fall 2016



# **Important Information**

- My contact:
  - Office: MK612 Email: kaisun@utk.edu Tel: 865-9743982
- Lectures:
  - 9:05-9:55AM on MWF at MK405
  - August 17 November 29 (about 40 lectures)
- 3 lab exercises: TBD in MK227
- Office hours:
  - Wed 10-11am (after the class) at MK612 or by appointment
- GTA:
  - Wenyun Ju (MK 209 <u>mxxu30@vols.utk.edu</u>)

## **Textbook and References**

- Main Text:
  - Wildi, *Electrical Machines, Drives and Power Systems (6<sup>th</sup> Ed)*, Prentice Hall, 2005
- Reference:
  - H. Saadat, Power System Analysis (3<sup>rd</sup> Ed), McGraw-Hill, 2010 (ECE421/422 text)





### **Course Outline**

- Prerequisite: ECE 202 Circuits II
  - Operational amplifiers, average, <u>complex</u>, imaginary and real power; effective values of voltage and currents, three phase circuits, delta and wye connections. Complex frequency; sinusoidal forcing functions and natural response. Resonance: general case, special cases in series and parallel circuits. Scaling: magnitude and frequency. Mutual inductance, transformers as circuit elements; linear and ideal transformers. Admittance, impedance and hybrid parameters. Trigonometric and complex Fourier series.
- Course Objectives:

Upon completion of this course, every student should have gained:

- 1. A broad familiarity with the fundamental principles of basic electric energy system components.
- 2. An understanding of the equipment needed for generation and delivery of bulk electric energy and basic steady-state analysis methods for power systems.

### **Course Outline (cont'd)**

- 1. Introduction to power systems: history, power industry, generation, transmission & distribution of energy (Ch. 24, 25.0-25.1, 26&notes)
- 2. Electrical circuits: circuits, AC power, phasors, 3-phase systems (Ch. 2,7&8) <u>Test 1 in mid-September</u>
- 3. Magnetic circuits: rotational motion, magnetic circuits (Ch. 2)
- 4. Transformers: ideal and practical transformers, per-unit system (Ch. 9-12)
- Transmission lines: parameters, models, equivalent circuit (Ch. 25) <u>Test 2 in mid-October</u>
- 6. Machines: induction machines, synchronous machines, motors (Ch. 13-17)
- 7. Power electronics: diodes, thyristors, switching converters (Ch. 21)
- Overview of power system analysis and introduction of real problems (notes)
   <u>Final Exam</u>

#### **Three laboratory exercises:**

- transformer voltage regulation
- induction motor
- synchronous motor

## **Course Requirements**

- Occasional quizzes (short-answer) given in class.
- 7-8 homework assignments and 3 lab exercises
  - Given in class and posted on the course website (<u>http://web.eecs.utk.edu/~kaisun/ECE325/</u> or google "Kai Sun UTK" for my homepage to find the course link)
  - you may work together in groups but must hand in your own homework solution and lab report.
- Three closed-book tests (only bring a calculator and two doubleside, letter-size summary sheets).
- For students who registered this course with Honors-by-Contract: a course project will be assigned (TBD).

# Grading

Homowork & Ouizzos	25%	A (90 and up)
• HOITIEWOIK & QUIZZES.	ZJ/0	A- (85-90)
<ul> <li>Laboratory Exercises:</li> </ul>	10%	
•Test 1:	20%	B+ (80-85)
•Test 2:	20%	B (76-80)
• <u>Final Exam</u>	25%	B- (72-76)
•Total	100%	C+ (68-72)
		C (64-68)
Finish all 3 lab exercises and at least 6 homework assignments for passing the course		C- (60-64)

 Submission delayed by >1 week receive up to 80% of points. The very final deadline is the day before the final exam.

# **Introduction to Power Systems**

- History of US Electric Industry
- Demand, generation, transmission & distribution of electric power
- Job Markets

Sources:

- Empires of Light: Edison, Tesla, Westinghouse, and the Race to Electrify the World, by Jill Jonnes, Random House, NY, 2003
- Dr. Robert B. Schainker's presentation "Pictorial History of the Development of Electricity" at EPRI in 2003
- Wildi's Chapters 24-26
- <u>NERC.com</u>, <u>Wikipedia.org</u>, and other websites

#### **Big Names Who Developed the Field of Electricity**

Big Names (Ordered by DOB)	Achievements
Benjamin Franklin (1706-1790), American	Lightning rod, Charge conservation
Charles A. de Coulomb (1736-1806), French	Coulomb's law
James Watt (1736-1819), Englishman	Steam engines, concept of power
Count A. Volta (1745-1827), Italian	Battery
Andre' M. Ampere (1775-1827), Frenchman	Electromagnetism, Ampere's law,
Hans C. Orsted (1777-1851), Danish	Electromagnetism
Carl F. Gauss (1777-1855), German	Gauss's law
George S. Ohm (1789-1854), German	Ohm's law
Michael Faraday (1791-1867), Englishman	Electromagnetic induction
Joseph Henry (1797-1878), American	Self- and mutual- inductance
James P. Joule (1818-1899), Englishman	Energy, Joule's first law
Gustav R. Kirchhoff (1824-1889), Prussian/German	Kirchhoff's circuit laws
James C. Maxwell (1831-1879), Scotsman	Electromagnetic field, Maxwell's equations
George Westinghouse (1846-1914), American	AC power system
Thomas A. Edison (1847-1931), American	Incandescent light bulb, DC power system
Nikola Tesla (1856-1943), Croatian/American	AC induction motor & transformer, AC power system
Heinrich Hertz (1857-1894), German	Electromagnetic waves
William Stanley, Jr. (1858-1916), American	New transformer design still used today, other devices
Charles P. Steinmetz (1865-1923), German/American	Mathematical theories for AC power systems

## **1831: World's 1<sup>st</sup> Electric Dynamo by Faraday**

• August 29, 1831: Faraday demonstrated how to make electricity from a change in magnetism









(Source: Wikipedia.org)

### 1876: World's 1st R&D Lab by Thomas Edison

- Founded in 1876 at Menlo park, NJ when Edison was 29 years old.
- Edison's team on the front steps of the lab building (Circa 1880).

<u>Top row (standing), left to</u> <u>right</u>: Albert Herrick, Francis Jehl, Samuel Edison (Edison's father), George Crosby, George Carman, Charles Mott, John Lawson, George Hill, Ludwig Boehm.

<u>Middle row</u>: Charles Batchelor, Edison, Charles Hughes, William Carman.

<u>Bottom row</u>: William Holzer, James Hipple.





## **1879: 1st Commercially Practical Incandescent Light** (by Edison)



First successful light bulb model, used in public demonstration at Menlo Park, December 1879

(source: Wikipedia.org)



Edison and his Menlo Park crew (taken in 1880, soon after new lights were installed)

### **1882:** 1st Commercial Power Plant for a City (by Edison)



- 3-floor Pearl Street Generation Station in NYC (commissioned on Sept. 4, 1882)
  - Had 6 coal-fed steam locomotive engines powering 6 direct current dynamos
  - Served 59 customers (all incandescent lamps at 110V through underground) cables) within a 1.5km radius area. (Motor loads were added to such systems after 1884) 13





Thomas Edison at his desk dictating into the "Edison Business Phonograph"

 By the time Edison was in his mid-30s, he was said to be the bestknown American in the world

- Edison has more patents (1,093) in his name than any other person, including:
  - 389, Electric Light & Power
  - 195, Phonograph
  - 150, Telegraph
  - 141, Storage Batteries
  - 34, Telephone
  - Kinetograph Motion Camera
  - Kinetoscope Motion Viewer
  - Magnetic Ore Separator

### 1<sup>st</sup> Home To Be Lit By Electricity



- J.P. Morgan Financial backer of Edison Electric Light Co., which later became General Electric Co.
- His home was the first home to be lit by electricity in the world using Edison's new light bulbs, powered by an Edison DC dynamo in the home basement.



### Nikola Tesla

- Rotating Magnetic Principle
- Polyphase AC Generators,
- Motors, and Grid Equipment
- AC Induction Motor
- Practical Wireless Communication
- Tesla High Voltage Coil
- Telephone Repeater
- 700 Other Patents



Nikola Tesla in the lab he set up in Colorado Springs (1899) to study electric energy by generating millions of volts (note: the photo is a double exposure.)

#### Tesla's bio in IEEE paper template



Nikola Tesla (M'1888, F'17) was born in Smiljan in the Austro-Hungarian Empire, on July 9, 1856. He graduated from the Austrian Polytechnic School, Graz, and studied at the University of Prague.

His employment experience included the American Telephone Company, Budapest, the Edison Machine Works, Westinghouse Electric Company, and Nikola Tesla Laboratories. His special fields of interest included high frequency.

Tesla received honorary degrees from institutions of higher learning including Columbia University, Yale University, University of Belgrade, and the University of Zagreb. He received the Elliott Cresson Medal of the Franklin Institute and the Edison Medal of the IEEE. In 1956, the term "tesla" (T) was adopted as the unit of magnetic flux density in the MKSA system. In 1975, the Power Engineering Society established the Nikola Tesla Award in his honor. Tesla died on January 7, 1943.



"Nikola Tesla" (by David Bowie) in movie *The Prestige* (2006) (*Source: IMDb.COM*)

## George Westinghouse: One Of the Few Who Appreciated the Practical Importance Of Tesla's Polyphase Patent



- An entrepreneur having the ability to transform <u>new ideas</u> to <u>commercial</u> <u>reality</u> while allowing for <u>relatively</u> <u>simple maintenance practices</u>
  - Invented railroad air brake and signaling equipment; had many patents on natural gas piping systems & equipment
  - Bought numerous electricity patents from Tesla
  - Commercialized AC generation & transmission systems
  - Battled Edison over AC vs. DC
  - Generation & grid applications
  - Provided Tesla with financial supports

#### Westinghouse-Tesla Polyphase Exhibit In The "Electricity Building" At The Chicago World's Fair (1893)



• Westinghouse's AC bid won over GE's DC bid for the fair's power & lighting contract.

WESTINGHOUSE ELECTRIC & MANUFACTURING CO. TESLA POLYPHASE SYSTEM





### **1st Westinghouse Generator**





Most of the patents cited above were from Tesla

- One of the 1<sup>st</sup> Westinghouse Niagara Falls Power Company generators being built in Pittsburgh in 1894 (Note: Westinghouse won this contract over a bid from GE.)
- This machine was a two phase, 25 Hz AC generator (3.8MW), the largest generator in the World, at the Time.



First Three Westinghouse Generators in Stanford White's "Cathedral of Power" at Niagara Falls (Photo Taken April 6, 1896)

### The Success Story Of Westinghouse-Tesla Team

Transforming new ideas to commercial reality while allowing for relatively simple maintenance practices





Innovator (1888)

(1889-)

Competitor (1882)



Demonstration (1893)



Application (1893-1896)

### **Morgan and Tesla**

- In 1900 Morgan invested \$150,000 in the "Tesla Tower", a high power transatlantic radio transmission project.
- By 1903 Tesla had spent the initial investment without completing the project, and with Guglielmo Marconi already making regular transatlantic transmissions with far less expensive equipment, Morgan declined to fund Tesla any further.
- Tesla tried to generate more interest in the tower by revealing its capability of wireless electricity transmission, but the loss of Morgan as a backer, and the later 1907 financial crisis dried up any further investment





In 2007, a MIT group powered a 60W bulb wirelessly over 7 feet in the air between two coils resonating together at 9.9MHz. (source: MIT.com; google keyword "WiTricity") Wardenclyffe Tower (1901–1917), also known as the Tesla Tower, was an early wireless transmission tower designed by Nikola Tesla in Shoreham, New York and intended for commercial trans-Atlantic wireless telephony, broadcasting, and proof-of-concept demonstrations of wireless power transmission ( a more powerful version of wireless communication).

(Source: Wikipedia.org)

### **From Generator to Grid**





(Einstein was given a tour at an RCA wireless station in NJ in 1921; source: Wikipedia.org)

#### Charles Steinmetz

- A mathematician who invented AC system theories (e.g. on hysteresis, steady-state analysis and transients) for AC machine and network performance calculations
- Recognized as one of the great inventors and minds of the 1900's.

## From Generator to Grid (cont'd)



W. STANLEY, Jr. INDUCTION COIL.



- William Stanley, Jr, had 129 Patents for a range of products and electrical devices, including:
  - Transformer (new design still used today)
  - Inductor Alternator
  - Line Insulator
  - Line Switch
  - Vacuum (Thermos) Bottle

### **How Transformers Work?**



$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$
$$V = N \frac{d\Phi}{dt}$$

 $V_2$  can be larger or smaller than  $V_1$ It only works with AC!





Source: Alstom.com

## Why 3-phase AC?

- Generation and transmission adopt 3-phase because:
  - 3 wires for 3 loads (if balanced)
  - Power is 3-phase AC is constant, not in pulses as in 1-phase AC. Thus, more power is delivered and 3-phase motors run more smoothly







Single phase 3-phase 3-phase Why not 6 or 12? <u>http://www.youtube.com/watch?v=HqZtptHnC21</u>

### **Reasons for AC Winning over DC**

- Voltage levels can be easily transformed in AC systems, thus providing the flexibility for use of different voltages for generation, transmission and consumption
- To reduce transmission power losses (RI<sup>2</sup>) and voltage drops, voltage levels have to be high for long-distance power transmission. HVAC was easier to implement by means of transformers. (At present, the cross-over point for HVDC to be competitive is around 500km for overhead lines or 50km for underground/submarine cables.)
- AC generators and motors are much simpler than DC generators and motors (commutators are needed)

## 1<sup>st</sup> 100 Years of Electric Industry

- 1882: Pearl Street Station, the 1<sup>st</sup> DC system by Edison, operated in NYC
- 1886: Commercially practical transformer and AC distribution system developed by Stanley
- 1888: Development of poly-phase AC by Tesla started AC vs. DC battle
- 1889: 1<sup>st</sup> AC transmission line in the US (1-phase, 21km at 4kV in Oregon)
- 1893: 1<sup>st</sup> 3-phase line (2.3kV, 12 km by SCE) in North America; AC vs. DC battle ended when AC was chosen at Niagara Falls.
- 1912-1923: 1st 110kV and 220kV HVAC overhead lines
- 1950s: 345kV-400kV EHV AC lines by USA, Germany and Sweden
- 1954: 1<sup>st</sup> modern commercial HVDC transmission (96km submarine cable) in Sweden.
- 1960s: 735-765kV EHV AC in Russia, USA and Canada
- 1972: 1<sup>st</sup> thyristor based HVDC Back-To-Back system between Quebec and New Brunswick in Canada

#### AC/DC Hybrid: a Super Grid?



(Source: presentation by A.-A. Edris in 2007 at EPRI)





(Source: "GOBITEC and Asian Super Grid for Renewable Energies In Northeast Asia" by Fraunhofer Institute, 2014)

Demand Leveling (Time Zone & Climate Difference) Stable Supply (through regional interdependence) Fair Electricity Price



### **US Energy Resources for Electricity Generation**



#### **2014 U.S. ELECTRICITY GENERATION**

Electricity generation by fuel, 1990-2040 (trillion kilowatthours per year)



From <u>www.wikipedia.org</u> and <u>www.eia.gov</u>

## **Demand of an Electric Power System**



- •System load level:
  - Base (min.) load: 6GW.
  - Peak (max.) load: 15GW.
  - Intermediate loads: in between
- •Observations:
  - Daily demands of two seasons have similar patterns. Why?
  - Geographic location?

### **Load Duration Curve**



- Peak-generation plants:
  - Gas turbine plants & pumpedstorage hydropower plants
- Intermediate-power plants:
  - Quickly responding to changes in demand
  - Hydropower & some fossil plants
- Base-power plants:
  - 100% power output at all times
  - Nuclear & coal-fired power plants