ECEN 460, Spring 2026
Power System Operation and Control

Class 3: Generators and Machines, Part 1

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TPEC: Texas Power and Energy Conference

- On campus at the MSC
- February 8-10, 2026
- Free for TAMU students
- More info: tpec.engr.tamu.edu
- It’s not too late to submit a poster
- Bonus credit for 460 (extra 100 quiz)
  - Attend at least 8 paper presentations (two paper sessions)
  - Visit sponsor company booths
  - Turn in one page of notes on what you did, observed, and learned to the TPEC registration desk, with your name, UIN, and “ECEN 460 Spring 2026 – Return to Dr. Birchfield” at the top.

The Next Three Weeks

- How to model parts of the power system
- Three main parts we will focus on
  - Generation (this week Jan 20/22)
  - Transformers (next week Jan 27/29)
  - Transmission Lines (following week Feb 3/5)
- When we're done with this, we'll have all we need to start modeling a full power system

Things to Remember About Modeling

- Take a small, basic 1 Ohm resistor for a breadboard. 10,000 amps should give you 10,000 volts, right? V=IR? Don't try it. The circuit model is wrong.
- Models are always only an approximation of reality, and are dependent upon the assumptions that are made in making that model
- "All models are wrong, but some are useful." – George Box
- The engineer's job in doing analysis is more than just putting numbers into a model and getting results.
  - It is figuring out the appropriate model to use that will be useful (though still ultimately wrong), given the questions you're trying to answer.
  - What range of currents and voltages are we talking about? What time frame? Microseconds? Years? How accurately do we need the answer? The model will change
  - You should always be asking: What assumptions am I making and are they reasonable?
- There are lots of different power system component models, for different purposes, and all of them are ultimately "wrong" i.e., incomplete

Generators

- Sources of energy in the power system
  - Nuclear
  - Coal-fired steam
  - Gas
    - Gas turbine
    - Steam turbine
    - Combined Cycle
  - Hydro
  - Oil / Petroleum
  - Wind
  - Solar
  - Other

Synchronous Machines (Today) (Nuclear through Oil / Petroleum)

Power Electronics / Other (Thursday) (Wind, Solar, Other)

Machines: Generators and Motors

- Electric machines are used to convert energy
  - Generators: mechanical into electrical
  - Motors: electrical into mechanical
  - Many devices can operate in either mode, but are usually customized for one or the other
- Majority of electricity is generated using synchronous generators and some is consumed using synchronous motors
- Much literature on subject, and sometimes overly confusing with the use of different conventions and nomenclature

Stator and Rotor

- Stator
  - The part of the machine that does not move
  - Contains sets of windings or “armature windings” surrounding the rotor
- Rotor
  - Internal part of the machine that rotates
  - Separated from the stator by airgap
  - Also has one or more windings or “field windings”
  - There may be some electrical connection between the spinning rotor windings and the stator
  - Occasionally the rotor is a permanent magnetic, but this limits control of the machine

Main Types of AC Machines

- Synchronous
  - Rotor windings have dc current powered separately
  - Stator is connected to the machine terminals
  - In steady state, rotor speed stays in-synch with the electrical frequency (i.e., some constant multiple)
- Induction
  - Rotor windings are shorted through an impedance
  - Stator is connected to the machine terminals
  - In steady state, the rotor speed may vary from the electrical frequency according to a "slip"
- Both can be 1 phase or 3 phase

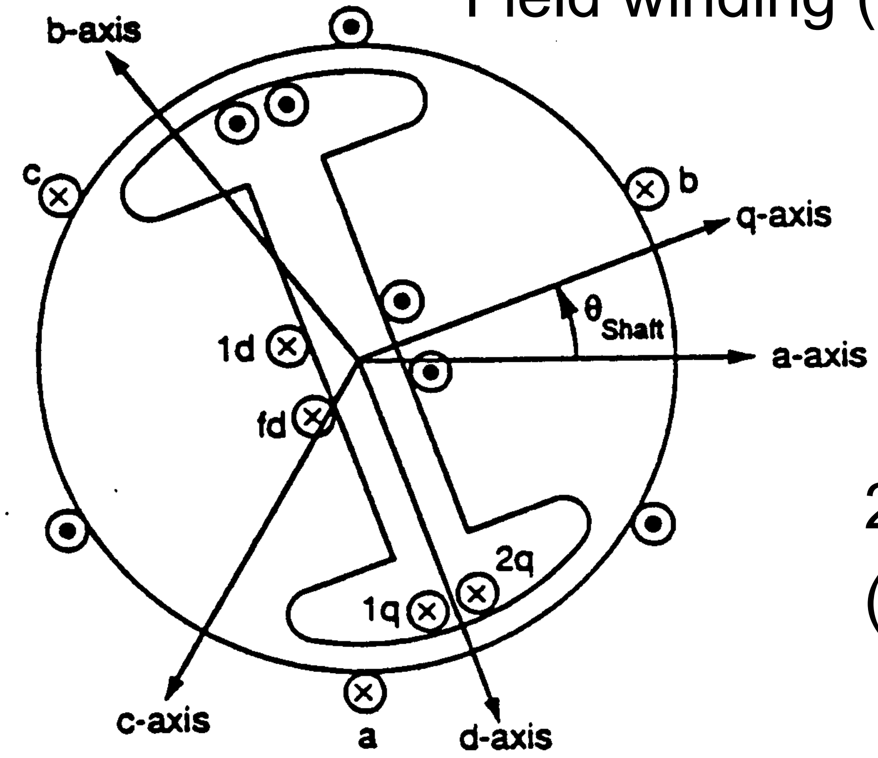
Three-phase Synchronous Machines

- Our focus today is on three-phase synchronous machines.
- The three stator windings have a three-phase voltage. In a motor or interconnected generator this voltage is supplied. In a stand-alone generator, it is induced.
- The stator ac electrical currents are arranged to create a rotating magnetic field.
- The rotor dc current creates a constant magnetic field which mechanically spins “in synch” with the stator field.

Diagram of Synchronous Machine

3ϕ bal. windings (a,b,c) – stator

Field winding (fd) on rotor



Damper in “d” axis (1d) on rotor

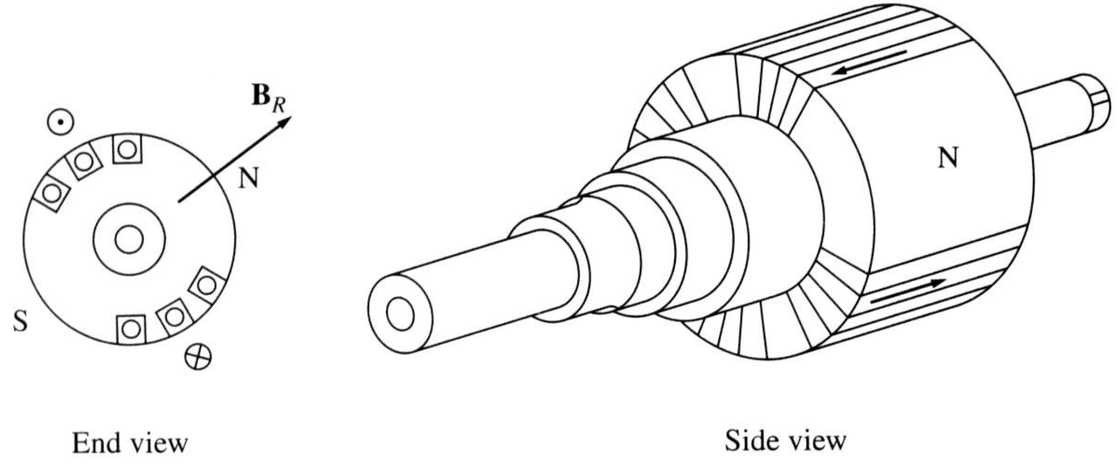
2 dampers in “q” axis (1q, 2q) on rotor

Round and Salient Pole Rotors

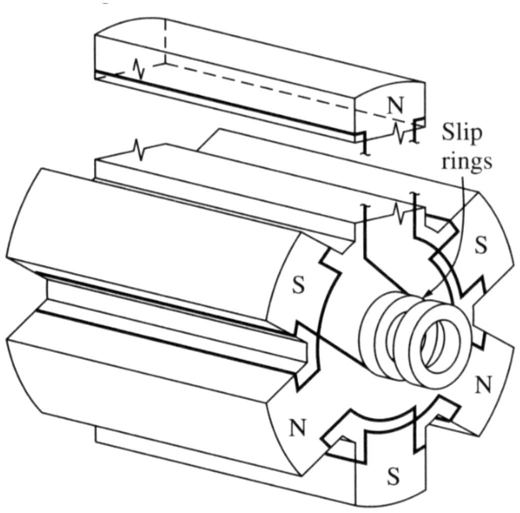
- Machines may have multiple pole pairs
- Rotor mechanical speed $= (f_s \times 120)/(\#$ Poles)
- With more poles, the rotor can spin slower than the stator electrical frequency f_s
- Round rotor
  - Air gap is constant, usually with higher speed machines
- Salient pole rotor
  - Air gap varies circumferentially
  - Used with slow, many-pole machines such as hydro

Rotor Examples

- Rotors are essentially electromagnets



Two pole (P) round rotor



Six pole salient rotor

Image Source: Dr. Gleb Tcheslavski, ee.lamar.edu/gleb/teaching.htm

Large Salient Rotor Example

High pole salient rotor

Shaft

Part of exciter, which is used to control the field current

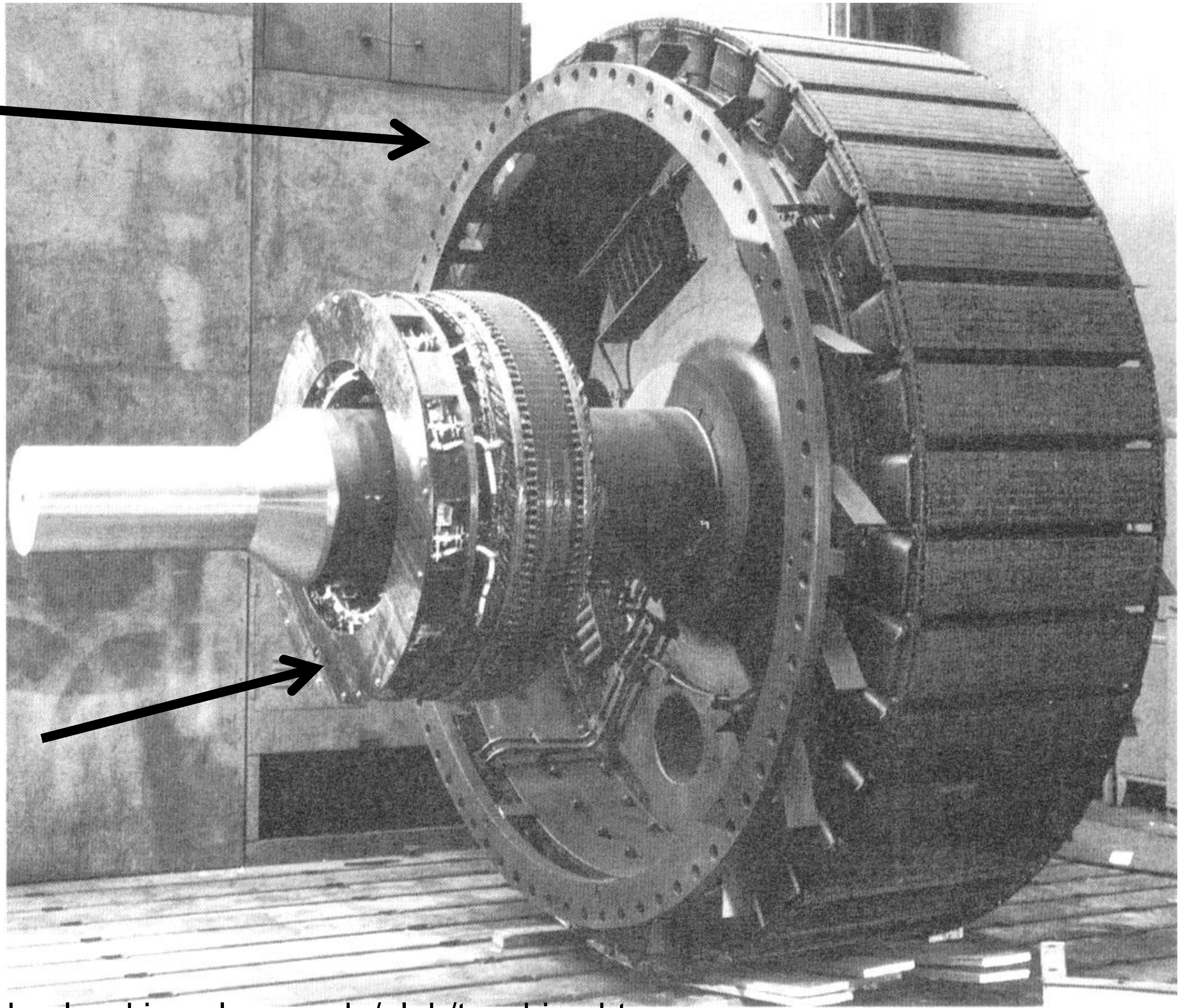


Image Source: Dr. Gleb Tcheslavski, ee.lamar.edu/gleb/teaching.htm

Creating a Voltage in an Open-Circuited Generator

- With zero stator current, the only magnetic flux is due to the field current
- When the generator is at standstill, the flux linking each coil depends on its angle relative to the rotor's position (and hence the field winding)
  - The three phases are physically shifted by 120 degrees from each other

$$\lambda_{aa'} = N\phi_{\max}\cos\theta = \lambda_{\max}\cos\theta$$

$$\lambda_{bb'} = N\phi_{\max}\cos\left(\theta - \frac{2\pi}{3}\right) = \lambda_{\max}\cos\left(\theta - \frac{2\pi}{3}\right)$$

$$\lambda_{cc'} = N\phi_{\max}\cos\left(\theta + \frac{2\pi}{3}\right) = \lambda_{\max}\cos\left(\theta + \frac{2\pi}{3}\right)$$

The maximum flux depends on the field current

Creating a Voltage in an Open-Circuited Generator, 3

- No voltage is generated at standstill
- Now assume the rotor is spinning at a uniform rate, $\omega = 2\pi f$ so

$$\lambda_{aa'} = N\phi_{max}\cos(\omega t + \theta_0) = \lambda_{max}\cos(\omega t + \theta_0)$$

$$\lambda_{bb'} = N\phi_{max}\cos\left(\omega t + \theta_0 - \frac{2\pi}{3}\right) = \lambda_{max}\cos\left(\omega t + \theta_0 - \frac{2\pi}{3}\right)$$

$$\lambda_{cc'} = N\phi_{max}\cos\left(\omega t + \theta_0 + \frac{2\pi}{3}\right) = \lambda_{max}\cos\left(\omega t + \theta_0 + \frac{2\pi}{3}\right)$$

Creating a Voltage in an Open-Circuited Generator, 4

- Then by Faraday's law a voltage is induced

$$e_{aa'} = \frac{d\lambda_{aa'}}{dt} = \lambda_{\max} \frac{d\cos\left(\omega t + \theta_0\right)}{dt} = -\lambda_{\max}\omega \sin(\omega t + \theta_0)$$

$$e_{bb'} = -\lambda_{\max}\omega \sin(\omega t + \theta_0 - \frac{2\pi}{3})$$

$$e_{cc'} = -\lambda_{\max}\omega \sin(\omega t + \theta_0 + \frac{2\pi}{3})$$

Creating a Voltage in an Open-Circuited Generator, 5

- For a linear magnetic circuit, we can also write this as proportional to field current

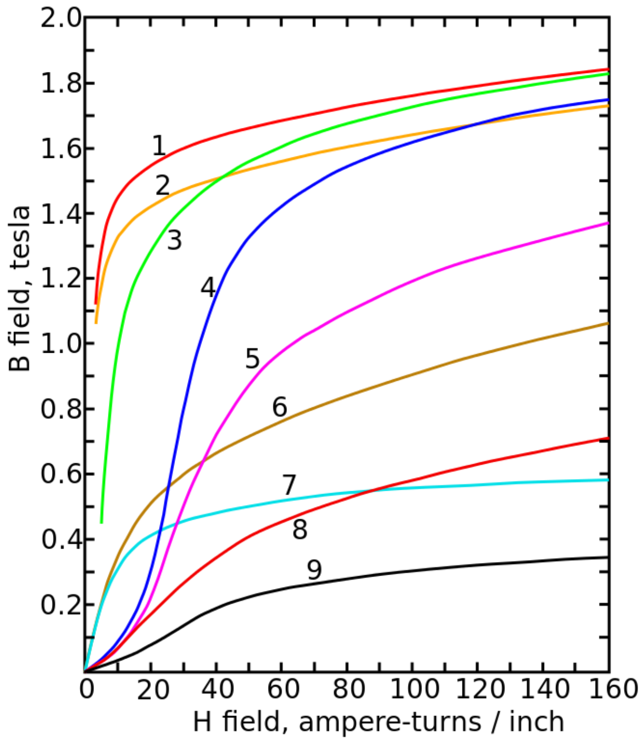
$$e_{aa'} = \frac{d\lambda_{aa'}}{dt} = -KI_f\,\omega\sin(\omega t + \theta_0)$$

Where K is a constant that depends on the machine construction, and I_f is the field current

The negative sign could be removed with a change in the assumed polarity

Magnetic Saturation and Hysteresis

- A linear magnetic circuit assumes the flux density B is always proportional to current, but real magnetic materials saturate



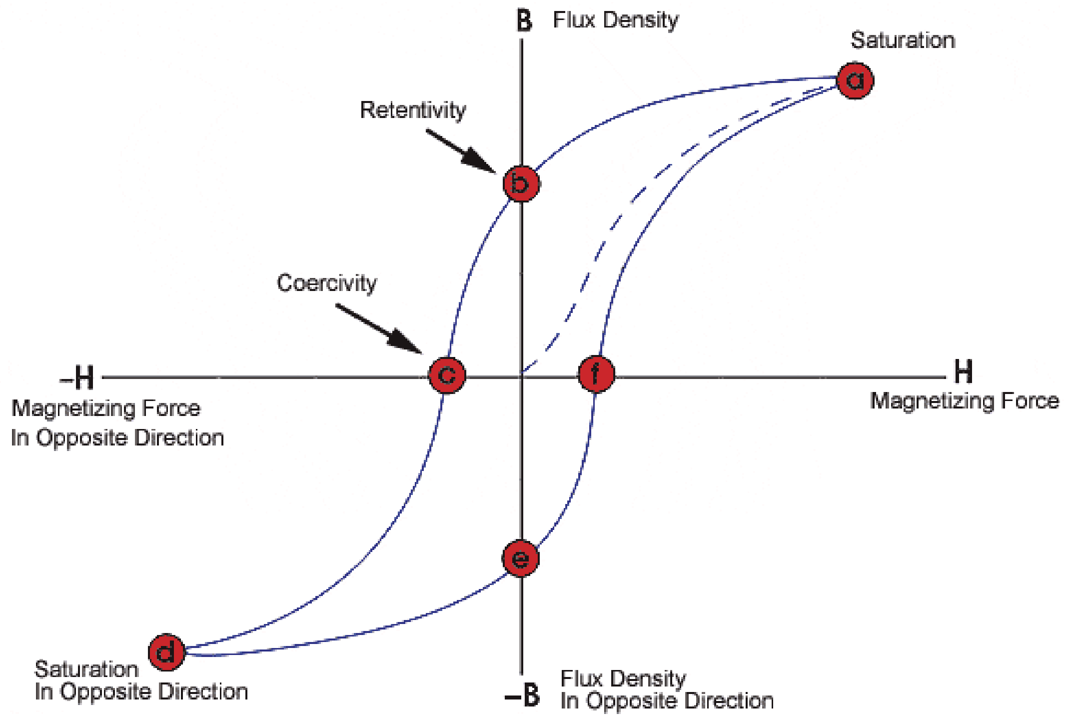
Magnetization curves of 9 ferromagnetic materials, showing saturation. 1.Sheet steel, 2.Silicon steel, 3.Cast steel, 4.Tungsten steel, 5.Magnet steel, 6.Cast iron, 7.Nickel, 8.Cobalt, 9.Magnetite; highest saturation materials can get to around 2.2 or 2.3T

H is proportional to current

Image Source: en.wikipedia.org/wiki/Saturation_(magnetic)

Magnetic Saturation and Hysteresis, 2

- Magnetic materials also exhibit hysteresis, so there is some residual magnetism when the current goes to zero; design goal is to reduce the area enclosed by the hysteresis loop



To minimize the amount of magnetic material, and hence cost and weight, electric machines
are designed to operate close to saturation

Image source: www.nde-ed.org/EducationResources/CommunityCollege/MagParticle/Graphics/BHCurve.gif

Frequency Impacts

- Assuming no saturation, the generated voltage is then proportional to frequency

$$e_{aa'} = \frac{d\lambda_{aa'}}{dt} = -N\phi_{\max}\omega\sin(\omega t + \theta_0) = -N\phi_{\max}2\pi\,\mathrm{f}\sin(\omega t + \theta_0)$$

- To create the same voltage with less flux, we just need to increase the frequency; this is why aircraft operate at a higher frequency (e.g., 400 Hz)
- When controlling motors with variable frequency, common control is to use constant volt/Hz, preventing saturation

Synchronous Machines with Output Current

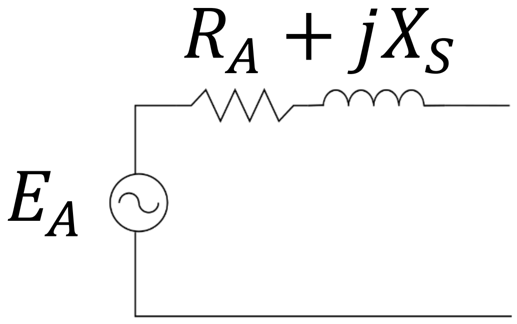
- When operating with an output current, the terminal voltage is not equal to the internally generated voltage
- This is due to several factors
  - Resistance in the stator windings
  - Self-inductance in the stator windings
  - Distortion of the air-gap magnetic field due to the stator current; that is, the stator current induces a magnetic field
  - Salient pole characteristics of the machine
- The stator reactance is called the synchronous reactance, X_s, and is sometimes broken into two parts

$$X_s = X_l + X_{ls}$$

X_l is due to the winding self inductance

A Synchronous Machine Model

- This gives us the following per phase model, which can be helpful in considering how the steady-state real and reactive output of the machine changes with changes in the field current



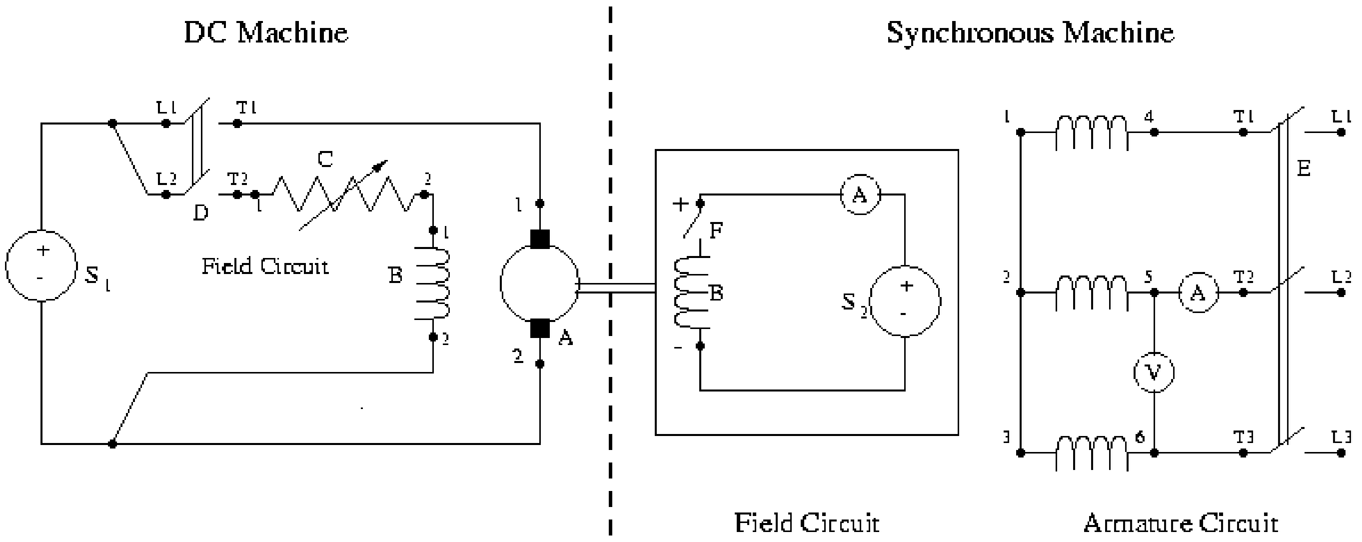
- This model is not particularly good for saturation and understanding the generator's dynamic response, something we'll revisit later

Synchronous Machine Testing to Determine its Parameters

- These synchronous machine parameters can be determined from two tests
  - Open-circuit test: measure the machine's response when there is no load, and the field current is gradually changed
  - Short-circuit test: measure the machine's response when it is operated at rated speed and its terminals are short-circuited

Lab 2 & 3 Setup

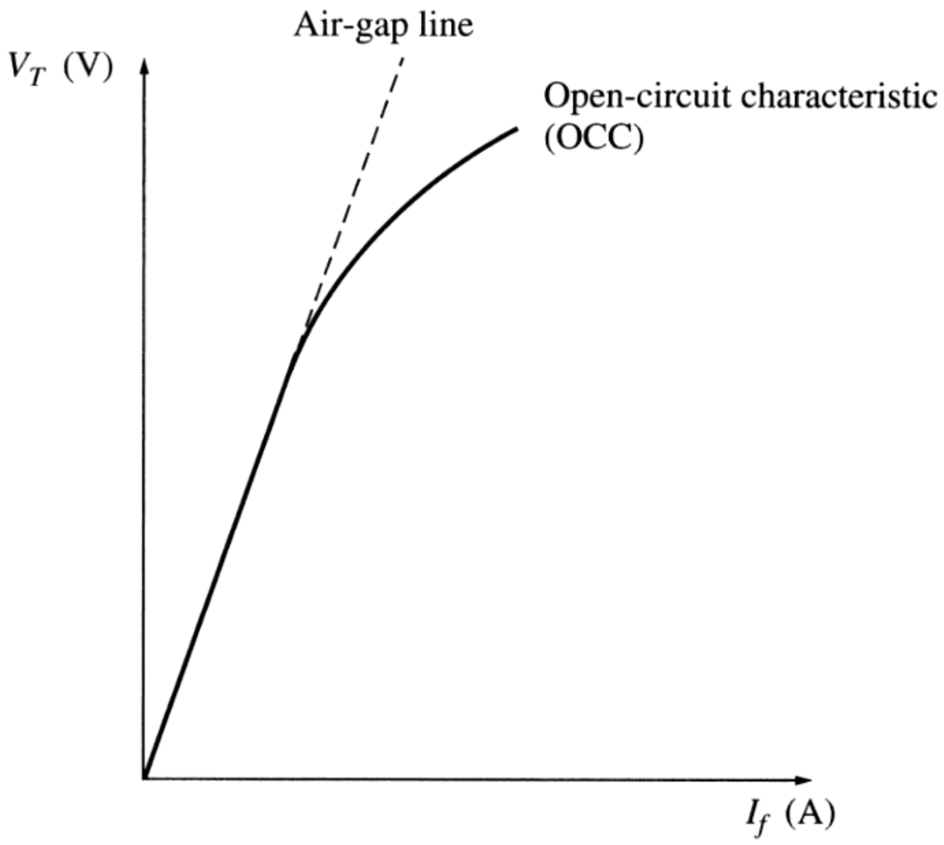
- We use a DC machine (which is speed controllable) to drive a synchronous generator. In lab 3 we do open-circuit and short-circuit tests to determine its parameters



In the experiment you measure line-to-line values, which are sqrt(3) times the line-to-neutral values

Open-Circuit Characteristic (OCC)

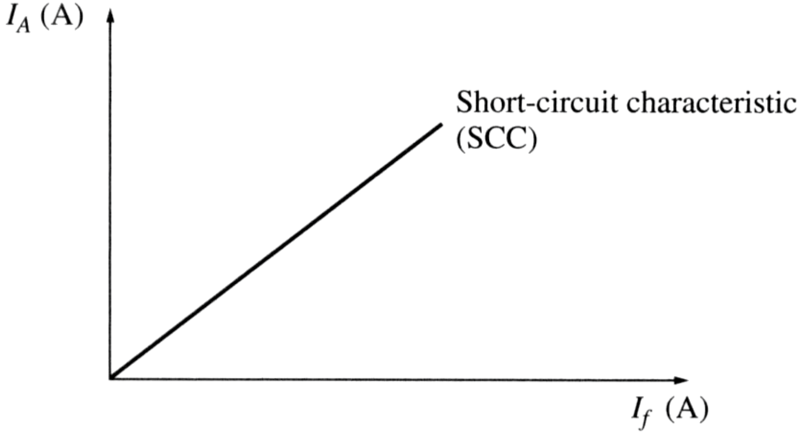
- The open-circuit characteristic (OCC) can be derived by gradually changing the field current when operating at a fixed frequency (e.g., synchronous speed)
  - Hysteresis needs to be considered when making field current adjustments
- Because there is no stator current, the internal voltage can be directly measured at the terminals
- We'll be using phasor values here



Short-Circuit Test

- The short-circuit characteristic measures the relationship between the field current and the terminal current
- With the model we get

$$I_{A,SC} = \frac{E_A}{\sqrt{R_A^2 + X_S^2}}$$



- Since usually XS >> RA, so

$$X_S \approx \frac{E_A}{I_{A,SC}}$$

This curve is almost linear since there is little saturation because the fluxes in the machine tend to cancel.

Short-Circuit Test, Cont.

- However, in doing this test we cannot directly measure EA and of course the terminal voltage is now zero during the short-circuit.
- One approach is to approximate it as

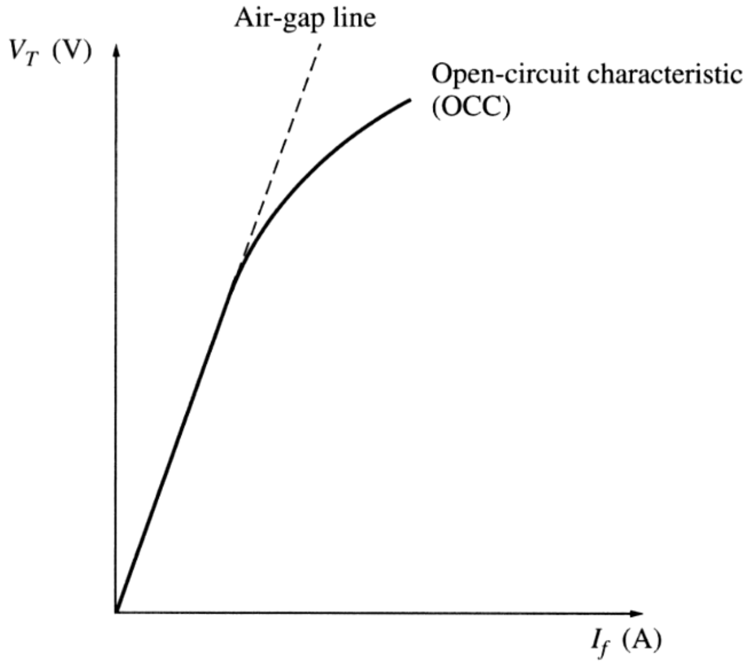
$$X_S \approx \frac{V_{OCC}}{I_{A,SC}}$$

where V_{OCC} is the measured open−circuit voltage at the same field current

Short-Circuit Test, Cont., 2

- This approach is accurate up to the point of saturation. An alternative approach is to substitute the equivalent air-gap voltage instead of the VOCC value.
  - This is commonly called the unsaturated synchronous reactance, Xu

$$X_u = \frac{E_{\text{agl}}}{I_{A,SC}}$$



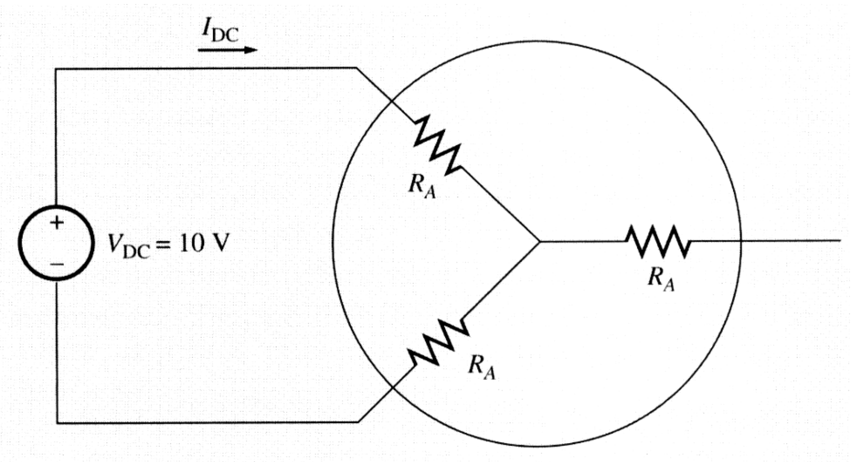
The amount of saturation depends on loading; in large generators saturation is explicitly modeled

Measuring RA

- The winding resistance can be calculated at standstill by applying a small dc voltage to two of the terminals, and then measuring the dc current

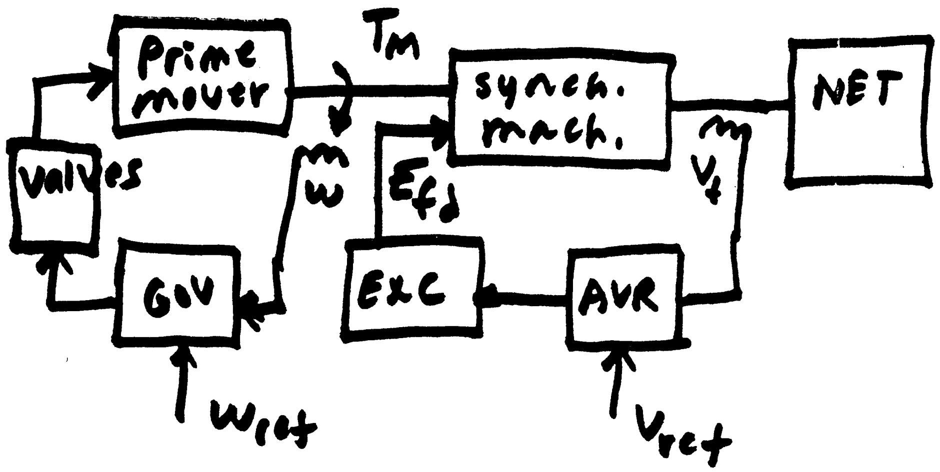
$$2R_A = \frac{V_{DC}}{I_{DC}}$$

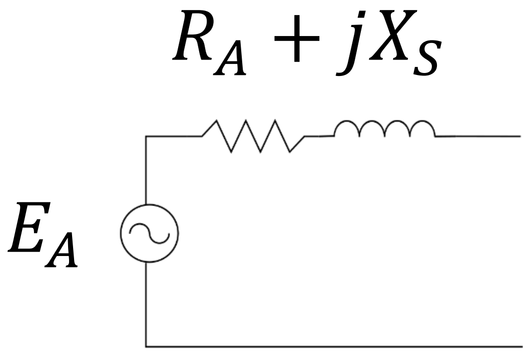
- Or one could just use an ohmmeter



Operating Synchronous Machines Under Load

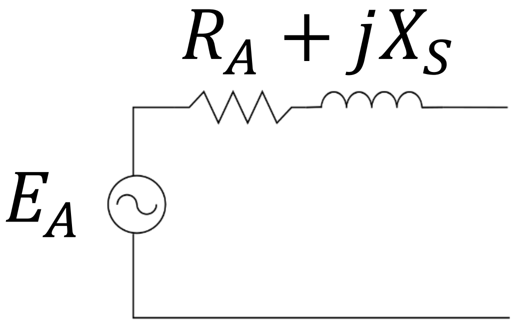
- We've seen that the terminal voltage of a synchronous machine can be controlled by adjusting its field voltage (and hence field current)
- Large generators have a number of automatic control systems, including one called an exciter to keep the terminal voltage or other voltage at a specified value
- Small machines might operate with a constant field current





Operating Synchronous Machines Under Load with a Constant Field

- If the field voltage and hence field current are assumed constant, and the speed is assumed constant (which in practice would be controlled by a governor), then the internal voltage can be assumed to be constant
- How the voltage varies with loading is then given by



$$E_A = V_T + (R_A + jX_s)I_A$$

or

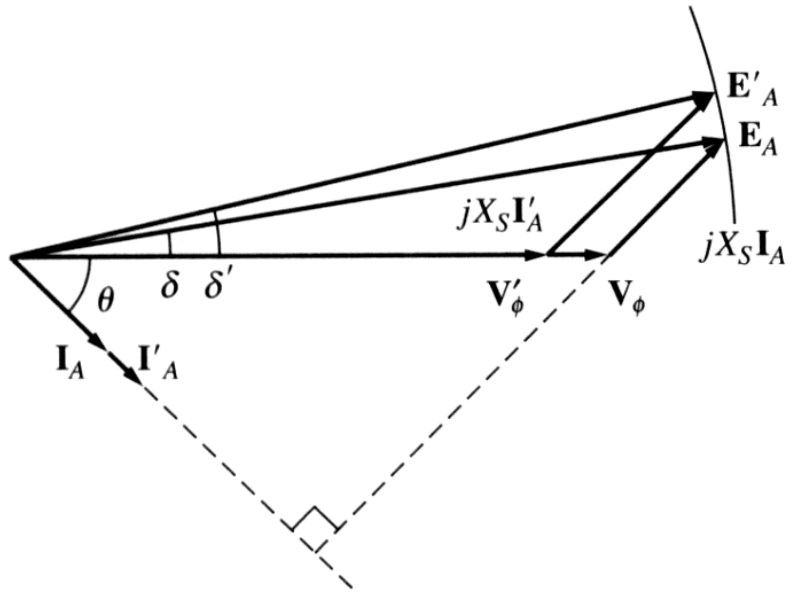
$$V_T = E_A - (R_A + jX_s)I_A$$

Operating Synchronous Machines Under Load with a Constant Field, 2

- To help gain insight, we'll neglect the usually small RA so then

$$V_T = E_A - jX_s I_A$$

  - Arbitrarily we can set the angle of VT to zero
- If the load has a lagging power factor then internal voltage magnitude is higher
- If leading pf then internal voltage is lower than the terminal voltage



Operating Synchronous Machines Under Load with a Constant Field, 3

- With R_A neglected, the power out of the machine is given by

$$P \frac{V_{T,pu} E_{A,pu}}{X_{s,pu}} \sin \delta_{out,\mathrm{pu}}$$

$$P_{3\phi} = 3 \frac{V_{AN} E_A}{X_s} \sin \delta$$

$$P_{3\phi} = \sqrt{3} \frac{V_{LL} E_A}{X_s} \sin \delta$$

δ is called the torque angle; in general, it is the angle difference between the internal voltage angle and the terminal voltage angle

$$P_{out,\mathrm{pu,max}} = \frac{V_{T,pu} E_{A,pu}}{X_{s,pu}} \qquad P_{3\phi,\mathrm{max}} = 3 \frac{V_{AN} E_A}{X_s}$$

Example

- A 200 kVA, 480 V (line-to-line), 60 Hz, Y-connected generator with a rated field voltage of 5A was tested with the following results
  - VT,LL = 540 V at rated field current
  - IA,SC = 300 A at rated field current
  - When disconnected, a dc voltage of 10 V is applied to two of the terminals, giving a current of 25 A
  - Find the model

$$2R_A = \frac{V_{dc}}{I_{dc}} = \frac{10}{25} \rightarrow R_A = 0.2\ \Omega$$

Example, Cont.

- The internal, per phase voltage is

$$E_A = \frac{540}{\sqrt{3}} = 311.8\ \mathrm{V}$$

- The synchronous reactance at the rated field current is

$$X_s \approx \frac{E_A}{I_{A,SC}} = \frac{311.8}{300} = 1.04\ \Omega$$

- If we wished to include the impact of RA it would be

$$X_s = \sqrt{\frac{E_A^2}{I_{A,SC}^2} - R_A^2} = \sqrt{\frac{311.8^2}{300^2} - 0.2^2} = 1.02\ \Omega$$

Example, Cont., 2

- Now assume a three-phase, wye-connected load is attached to its terminal with $Z = 4\angle 20^\circ\ \Omega$. The field current is adjusted so the line-to-line terminal voltage is 480 V and the generator is operated at 60 Hz. What is the internal voltage, and what is the total power delivered to the load? Use XS = 1.04 Ω. Then repeat with $Z = 4\angle -20^\circ\ \Omega$.

Example, Cont., 3

- With Z = 4∠20° Ω

$$I_A = \frac{\left(\frac{480}{\sqrt{3}}\right)\angle 0^\circ}{4\angle 20^\circ} = 69.3\angle -20^\circ$$

$$E_A = \frac{480}{\sqrt{3}}\angle 0^\circ + (0.2 + j1.04) \times 69.3\angle -20^\circ = 314.8 + j63.0 = 321\angle 11.3^\circ \text{ V}$$

$$S_{3\phi,load} = \sqrt{3} \times 480 \times 69.3\angle 20^\circ = 576\angle 20^\circ \text{ kVA}$$

- With Z = 4∠-20° Ω

$$I_A = \frac{\left(\frac{480}{\sqrt{3}}\right)\angle 0^\circ}{4\angle -20^\circ} = 69.3\angle 20^\circ$$

$$E_A = \frac{480}{\sqrt{3}}\angle 0^\circ + (0.2 + j1.04) \times 69.3\angle 20^\circ = 265.5 + j72.5 = 275\angle 15.3^\circ \text{ V}$$

$$S_{3\phi,load} = \sqrt{3} \times 480 \times 69.3\angle -20^\circ = 576\angle -20^\circ \text{ kVA}$$

DC Machines

- Prior to widespread use of machine drives, dc motors had an important advantage of easy speed control
  - Example is a model railroad
- On the stator a dc machine has either a permanent magnet or a single concentrated winding
  - With winding field voltage is Vf and field current is If
- Rotor (armature) currents are supplied through brushes and commutator

DC Machines, 2

- If there is a field winding (i.e., not a permanent magnet machine) then the machine could be connected in the following ways
  - Separately-excited: Field and armature windings are connected to separate power sources
    - For an exciter, control is provided by varying the field current (which is stationary), which changes the armature voltage
  - Series-excited: Field and armature windings are in series
  - Shunt-excited: Field and armature windings are in parallel

DC Machines, 3

- In a machine with a field winding the equations are

$$V_F = I_F R_F + L_F \frac{dI_F}{dt}$$
$$V_T = I_A R_A + L_A \frac{dI_A}{dt} + G\omega_m I_A$$

G is a machine constant, w_m is its speed

- In steady-state these can be simplified to

$$V_F = I_F R_F$$
$$V_T = I_A R_A + G\omega_m I_F$$

- In a shunt-connected machine, VT = VF so

$$V_T = I_A R_A + G\omega_m \frac{V_T}{R_F}$$