ECEN 460
Power System Operation and Control
Spring 2025

Lecture 23: Voltage Stability, Synchronous Machines, Wind and Solar

Prof. Tom Overbye
Dept. of Electrical and Computer Engineering
Texas A&M University
overbye@tamu.edu

Announcements

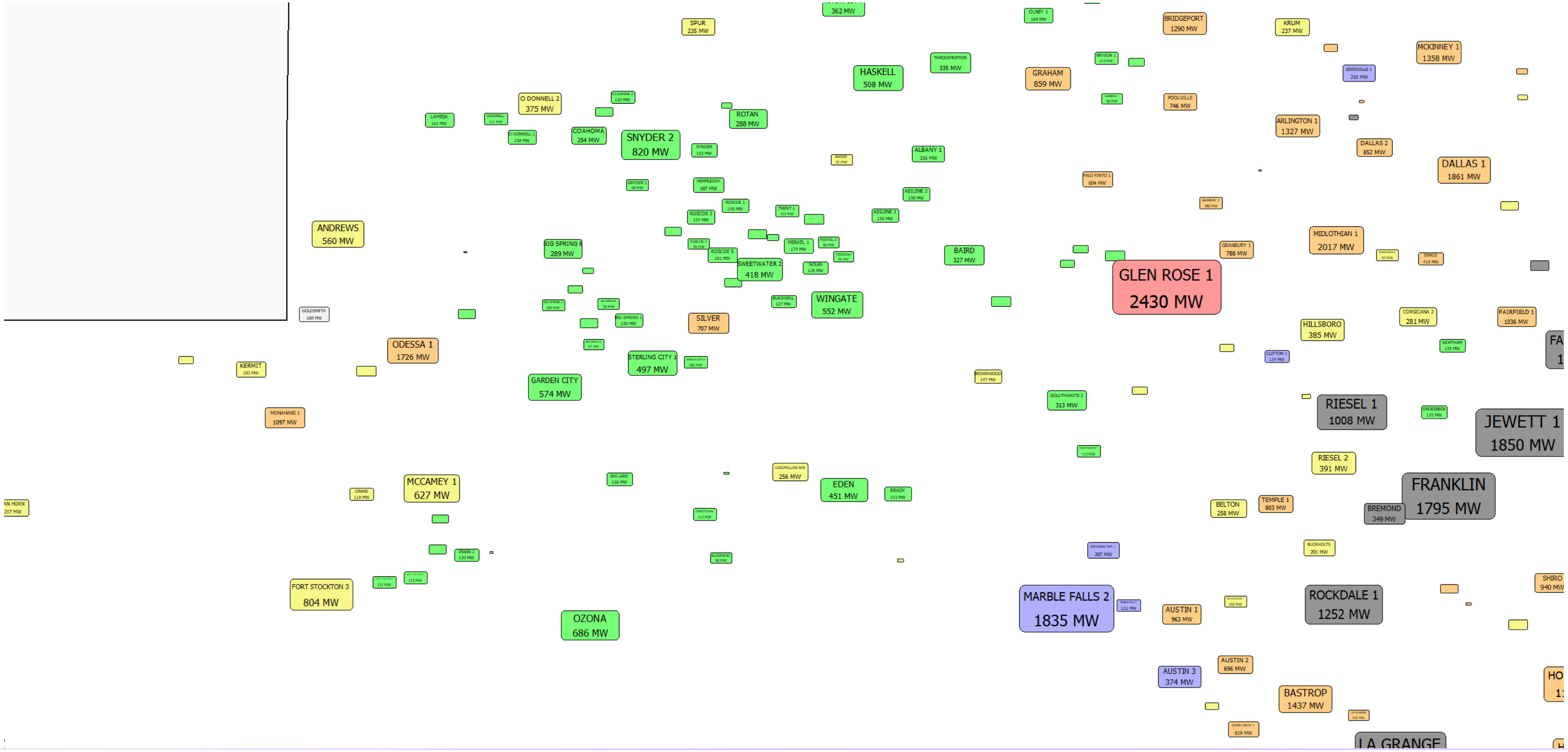
- Please read Chapter 13
- Schedule for the rest of the semester is
  - Design project progress reports due this week counting for 5% of total project grade
  - Design project loads have been corrected – see course announcment
  - Lab 3 week of April 14 is an optional, ungraded machine lab, Wednesday times only; Friday is a Reading Day so the Friday lab folks can go to a Wednesday lab
  - Lab 11 (project presentations) by the individual teams to their TA ideally before the end of classes (on or before April 29)
  - Exam 2 on Wednesday April 23 during class; similar format to other exam; comprehensive but more emphasis on material since the first exam; send me true, false questions for the exam
  - Design project due at 9:30 am on May 1 (i.e., at the end of our final slot; no final)

Project Comments and Questions

- For transmission lines and transformers, the terms "from" and "to" bus have been used in power flow formats since at least 1973; this is kind of confusing since power can flow in either directions
- Transformers must be located in a single substation. Power flow programs has traditionally allowed any buses to be connected regardless of distance or voltage levels
  - Equivalent lines could go between different voltage levels; also, geography is a relatively new addition to many power flow programs
- The issue with the "wandering" substation 2004 (with bus 3201) has been fixed, and the generator display has been updated to show the substation maximum MW generation values

ECEN 460 Design Project Generation

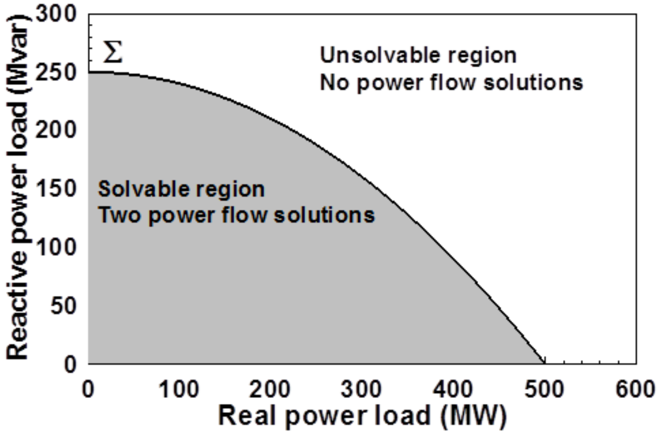
- The fossil and hydro generation is always available; in some scenarios you have very limited wind and solar generation



Note: for your design project Marble Falls 2 is modeled as being hydro generation; this is not the case for the actual grid

Determining a Metric to Voltage Collapse

- The goal of much of the voltage stability work was to determine an easy way to calculate a metric (or metrics) of the current operating point to voltage collapse
  - PV and QV curves (or some combination) can determine such a metric along a particular path
  - Goal was to have a path independent metric. The closest boundary point was considered, but this could be quite misleading if the system was not going to move in that direction



  - Any linearization about the current operating point (i.e., the Jacobian) does not consider important nonlinearities like generators hitting their reactive power limits

Assessing Voltage Margin Using PV and QV Curve Analysis

- A common method for assessing the distance in parameter space to voltage instability (or an undesirable voltage profile) is to trace how the voltage magnitudes vary as the system parameters (such as the loads) are changed in a specified direction
  - If the direction involves changing the real power (P) this is known as a PV curve; if the change is with the reactive power (Q) then this is a QV curve
- PV/QV curve analysis can be generalized to any parameter change, and can include the consideration of contingencies

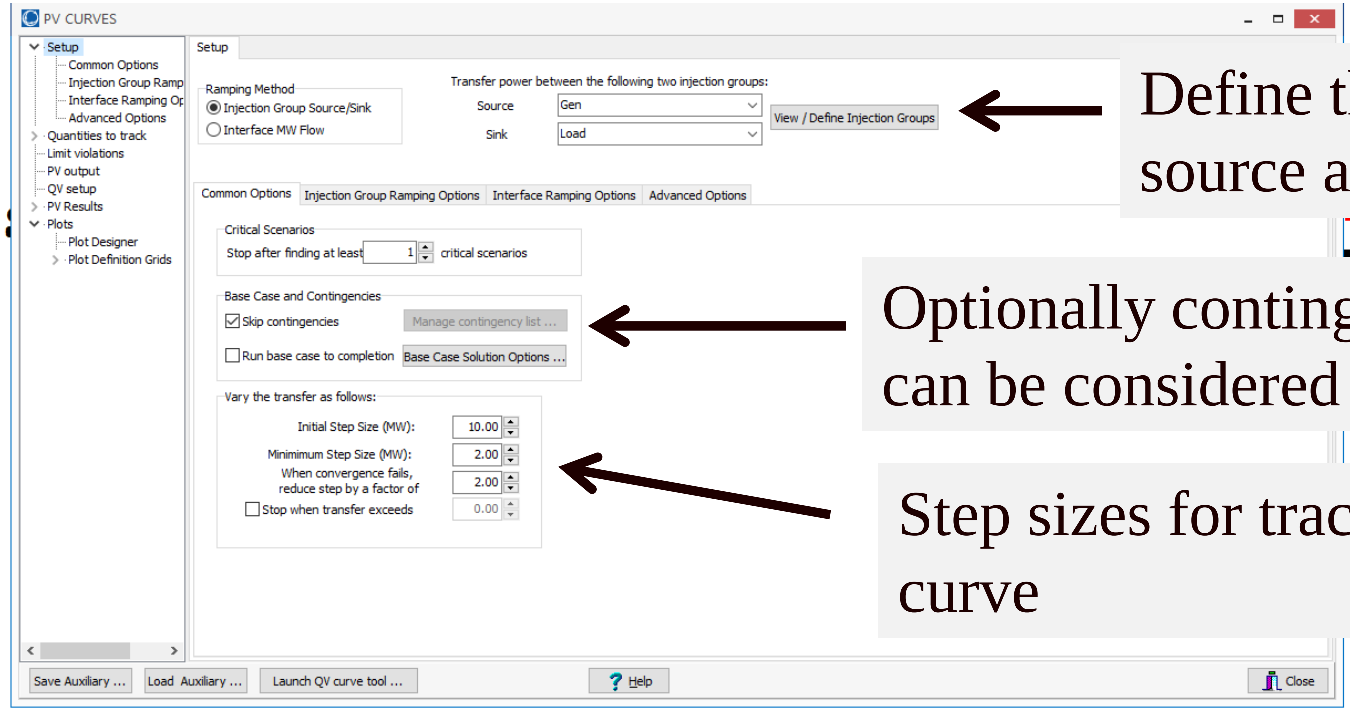
PV and QV Analysis in PowerWorld

- Requires setting up what is known in PowerWorld as an injection group
  - An injection group specifies a set of objects, such as generators and loads, that can inject or absorb power
  - Injection groups can be defined by selecting **Case Information, Aggregation, Injection Groups**
- The PV and/or QV analysis then varies the injections in the injection group, tracing out the PV curve
- This allows optional consideration of contingencies
- The PV tool can be displayed by selecting **Add-Ons, PV**

This has already been done in the **Bus2_PV** case

PV and QV Analysis in PowerWorld: Two Bus Example

- Setup page defines the source and sink and step size



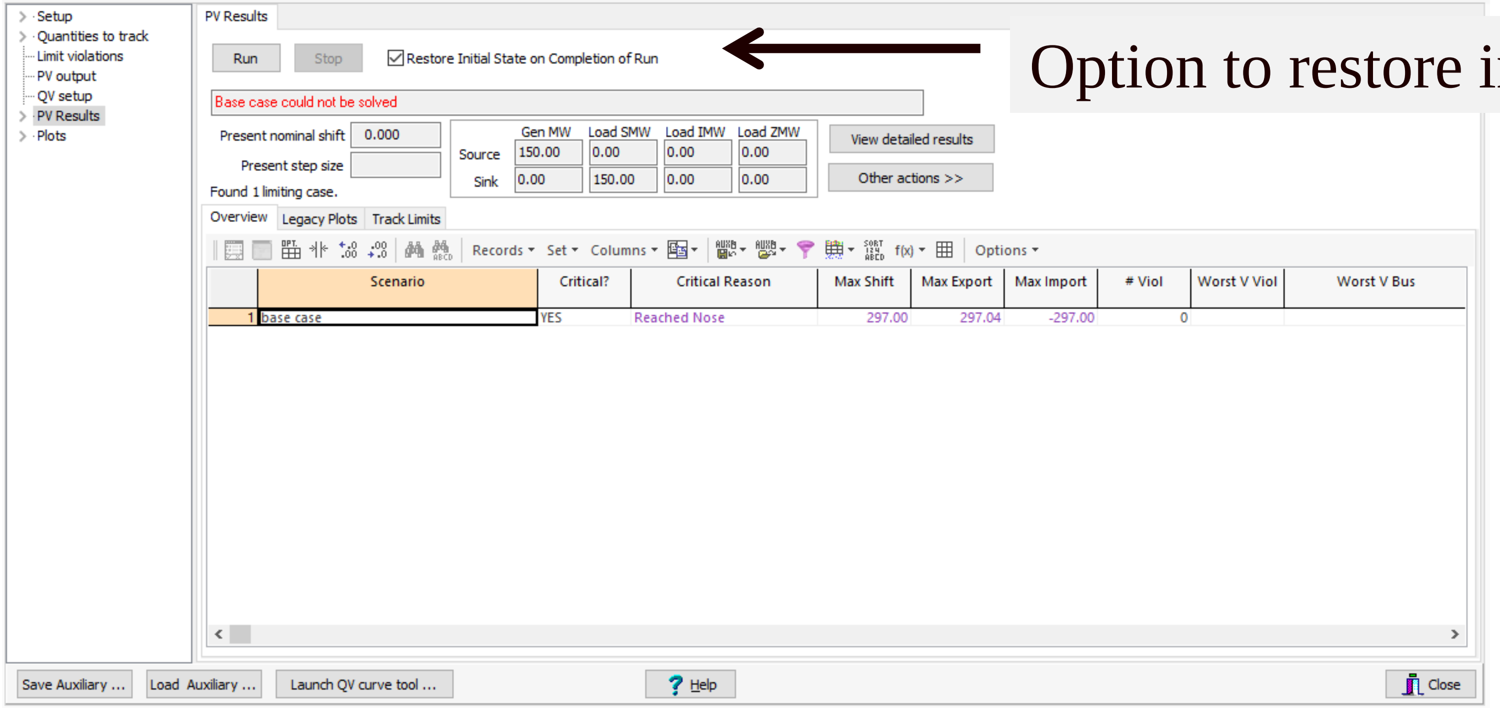
Define the source and sink

Optionally contingencies can be considered

Step sizes for tracing the curve

PV and QV Analysis in PowerWorld: Two Bus Example

- The PV Results Page does the actual solution
  - Plots can be defined to show the results
    - This should be done beforehand
  - **Other Actions, Restore initial state** restores the pre-study state

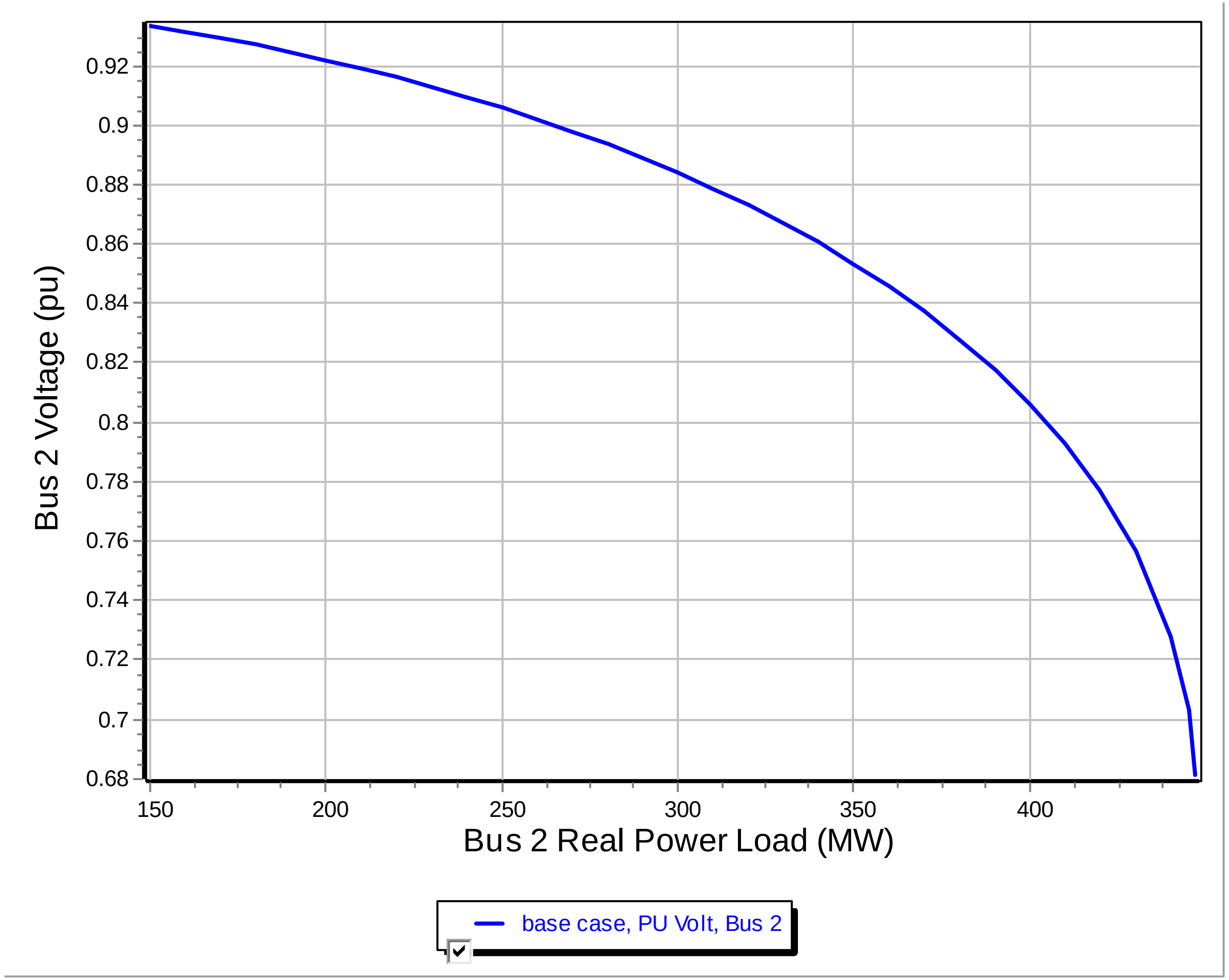


Option to restore initial state

Click the **Run** button to run the PV analysis;

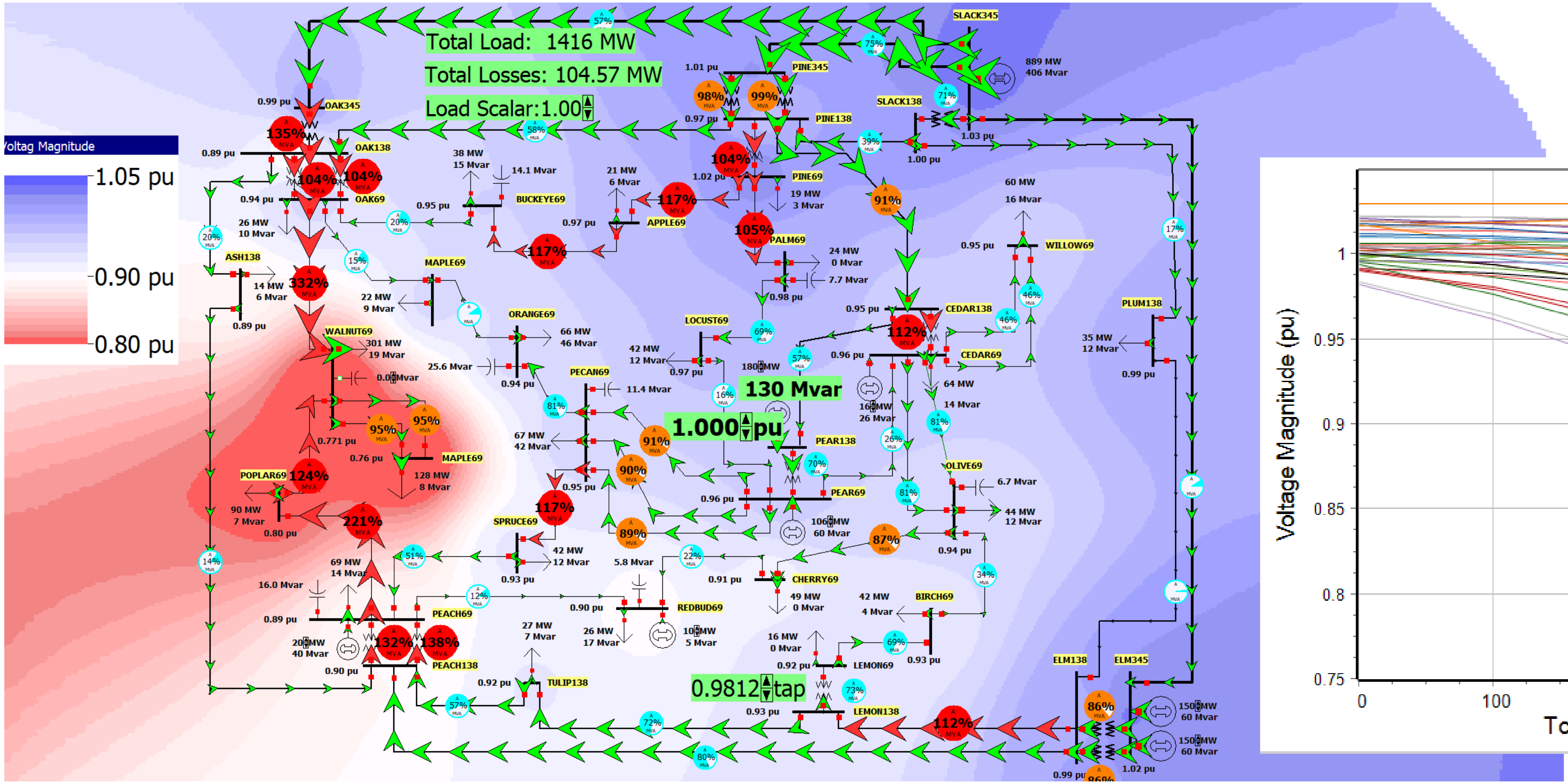
Check the **Restore Initial State on Completion of Run** to restore the pre-PV state (by default it is not restored)

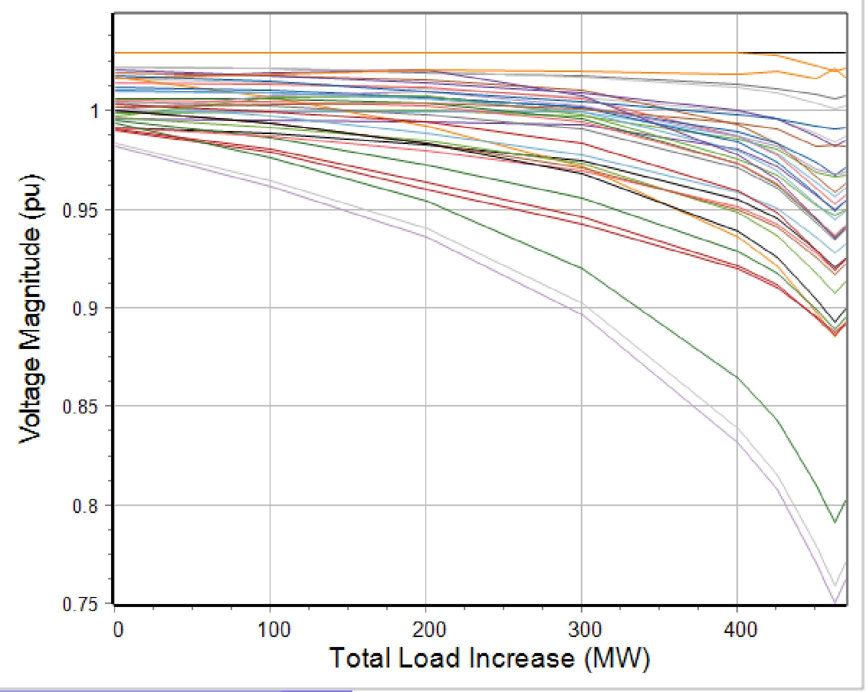
PV and QV Analysis in PowerWorld: Two Bus Example



To restore the starting case, on the **PV Results** page select **Other Actions, Restore Initial State**

PV and QV Analysis in PowerWorld: 37 Bus Example





Usually other limits also need to be considered in doing a realistic PV analysis; example case is **Bus37_PV**

Shorter Term Dynamics

- On a shorter time-scale (minutes down to seconds) voltage stability is impacted by controls hitting limits (such as the action of generator over excitation limiters), the movement of voltage control devices (such as LTC transformers) and load dynamics
  - Motor stalling can have a major impact
- The potential for voltage instability can be quantified by looking at the amount and duration of voltage dips following an event

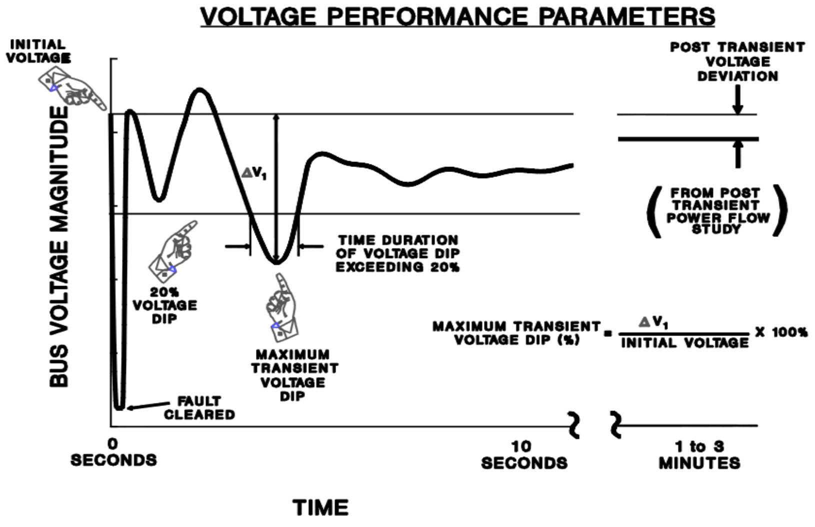


Image from WECC Planning and Operating Criteria

Dynamic Load Response

- As first reported in the below paper, following a change in voltage there will be a dynamic load response
  – Residential supply voltage should be between 114 and 126 V
- If there is a heating load the response might be on the order of ten minutes
- Longer term issues can also come into play

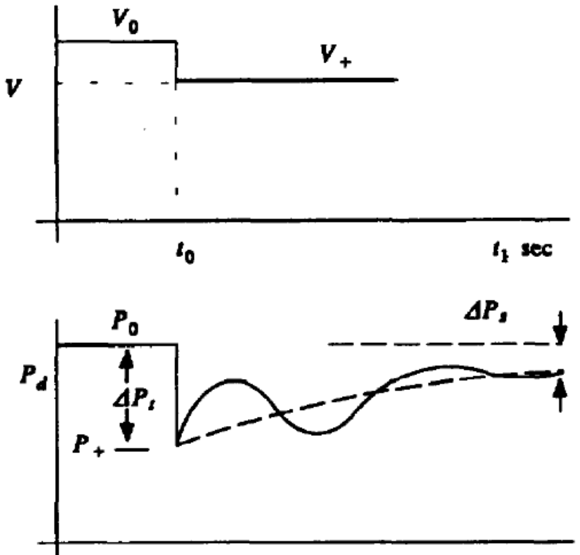


Figure 2.2 General Load Response

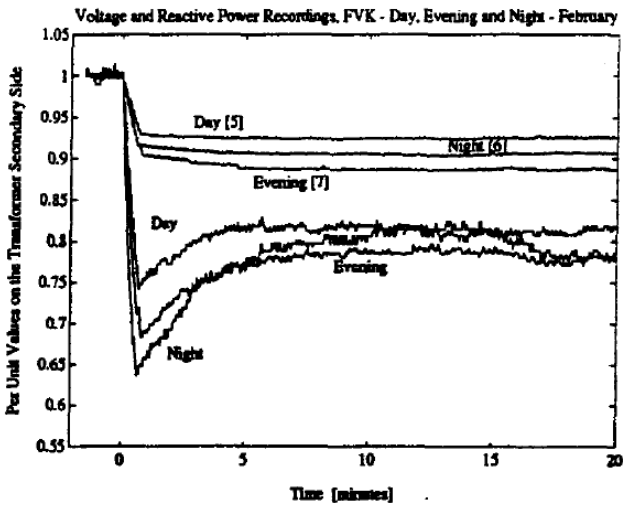


Figure 4.4b. Voltage and reactive power recordings after a voltage reduction in FVK: February; day, evening and night. The number of tap-changer steps used for the ramp is shown in brackets.

Useful paper and figure reference: D. Karlsson, D.J. Hill, “Modeling and Identification of Nonlinear Dynamic Loads in Power Systems,” IEEE. Trans. on Power Systems, Feb 1994, pp. 157-166

Fault Induced Delayed Voltage Recovery (FIDVR)

- FIDVR is a situation in which the system voltage remains significantly reduced for at least several seconds following a fault (at either the transmission or distribution level)
  - It is most concerning in the high voltage grid, but found to be unexpectedly prevalent in the distribution system
- Stalled residential air conditioning units are a key cause of FIDVR – they can stall within the three cycles needed to clear a fault

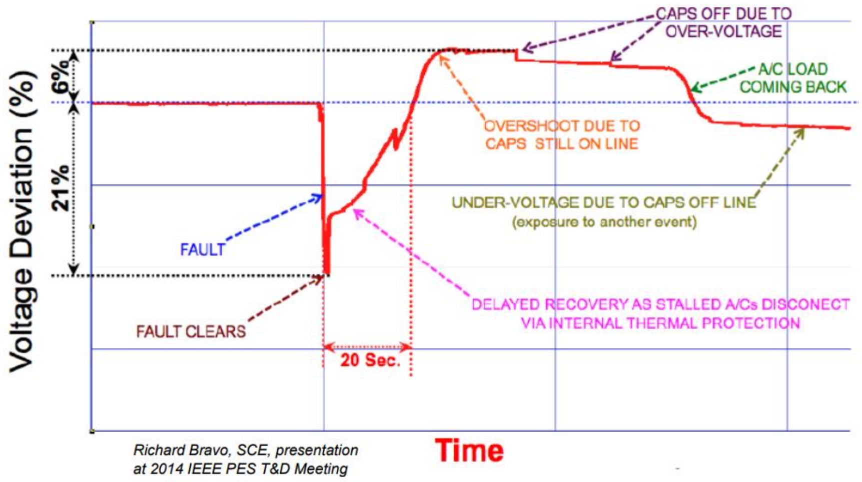


Image Source: NERC, Fault Induced Delayed Voltage Recovery (FIDVR) Advisory, July 2015

Application: Conservation Voltage Reduction (CVR)

- If the “steady-state” load has a true dependence on voltage, then a change (usually a reduction) in the voltage should result in a total decrease in energy consumption
- If an “optimal” voltage could be determined, then this could result in a net energy savings
- Some challenges are 1) the voltage profile across a feeder is not constant, 2) the load composition is constantly changing, 3) a decrease in power consumption might result in a decrease in useable output from the load, and 4) loads are dynamic and an initial decrease might be balanced by a later increase

CVR Issues

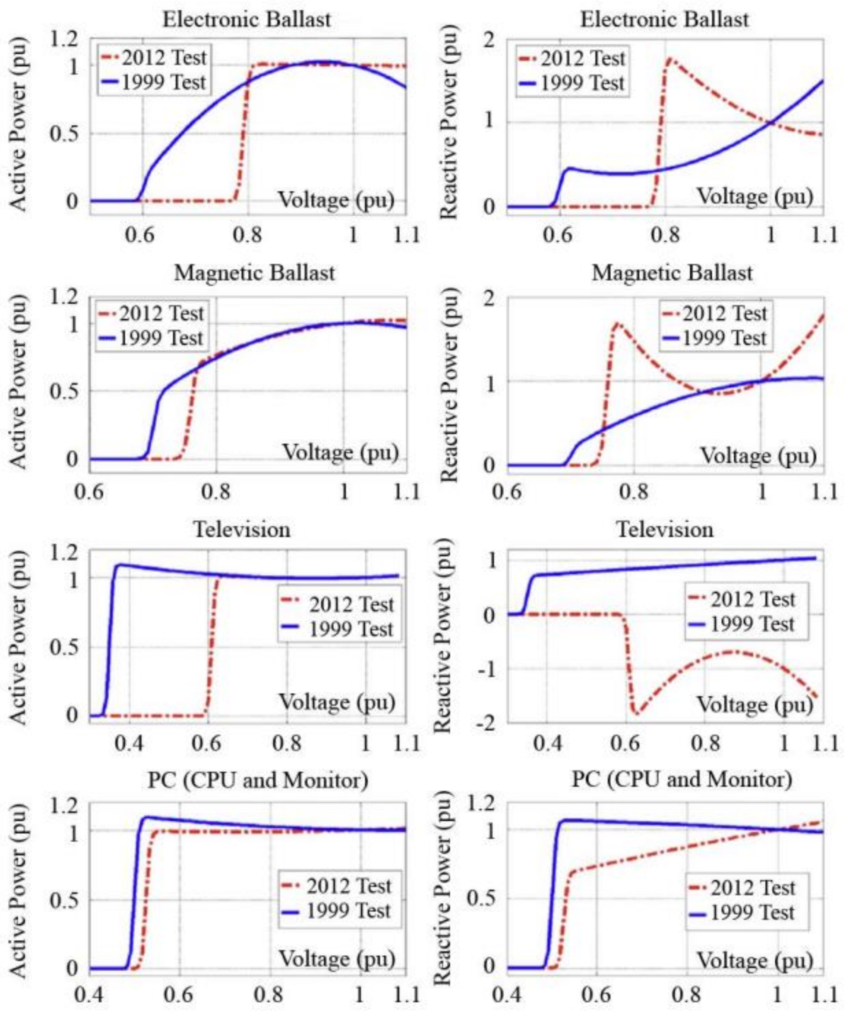
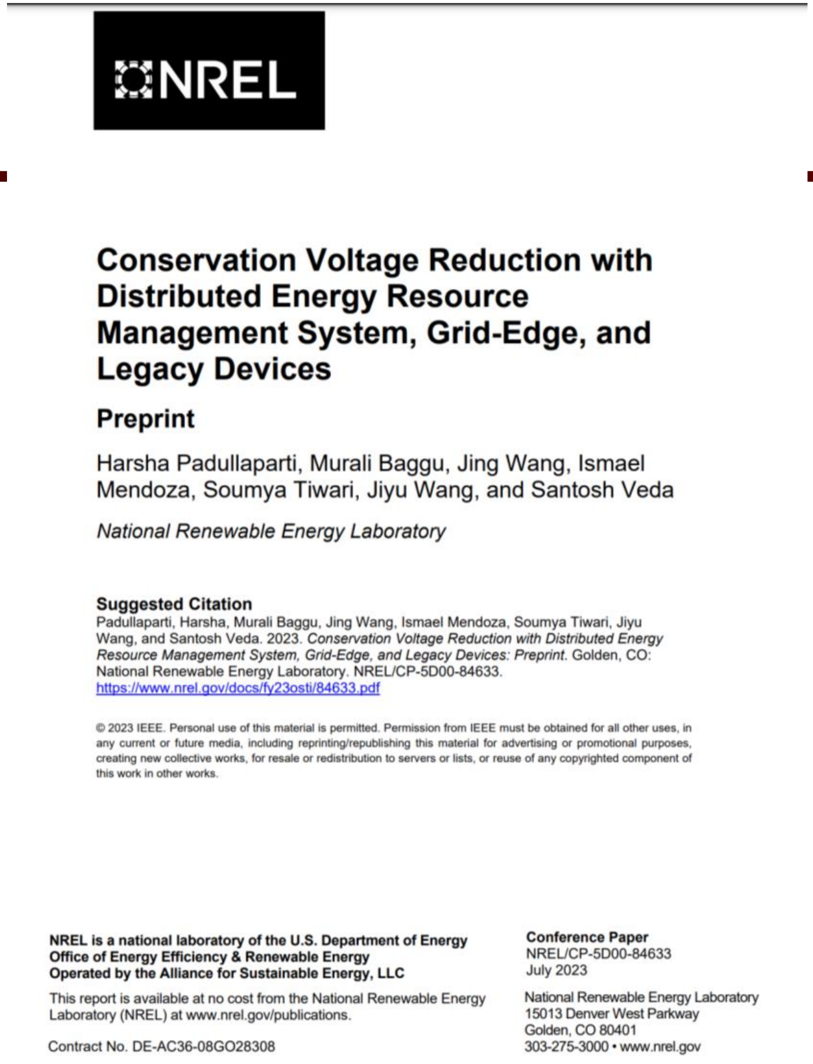


Fig. 4. Comparison of active and reactive powers between old and new appliances.



NREL

Conservation Voltage Reduction with Distributed Energy Resource Management System, Grid-Edge, and Legacy Devices

Preprint

Harsha Padullaparti, Murali Baggu, Jing Wang, Ismael Mendoza, Soumya Tiwari, Jiyu Wang, and Santosh Veda

National Renewable Energy Laboratory

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15013 Denver West Parkway
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Figure 4 from A, Bokhari, et. al., "Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial, and Industrial Loads," *IEEE Trans. Power Delivery*, June. 2014

The gist of the 2023 NREL paper is distributed generation (like PV) can help with CVR through better feeder voltage regulation

Lab 3 Background: Synchronous Machine Basics

- Two basic parts
  - Stator (or armature) is the stationary outside of the machine
  - Rotor is the internal part that rotates; as we covered with exciters, it has a dc field current that is used to produce a magnetic field
  - Stator and rotor are separated by an airgap, which is needed to allow the rotor to spin
- Synchronous machines are named because in steady state the rotor spins at a speed proportional to the electrical frequency (i.e., it stays in synch with the electrical frequency)
- Can be either three-phase or single-phase; we'll just consider three-phase machines

Rotation Speed and Two Main Types of Synchronous Machines

- Machines may have multiple pole pairs to spin at speeds slower than the electrical frequency

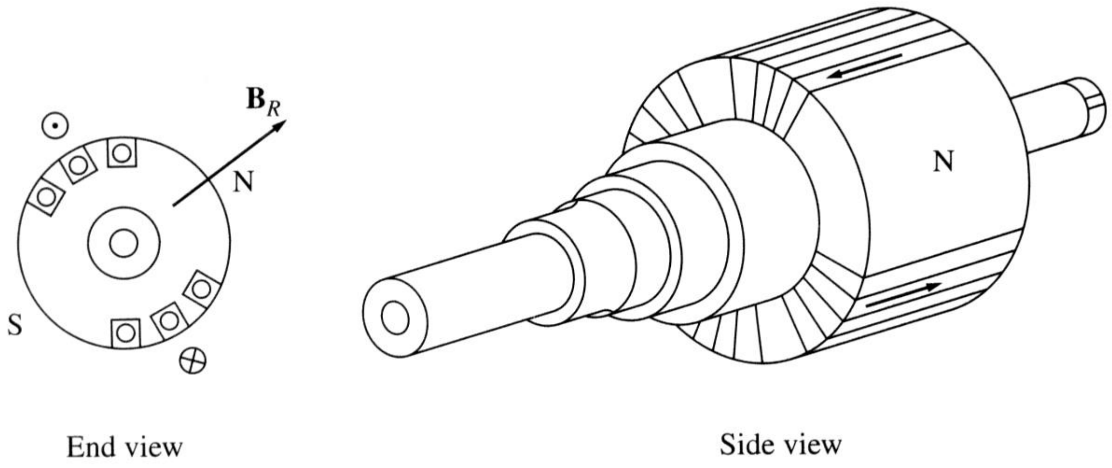
$$\frac{f_s \times 120}{P} = n_m$$

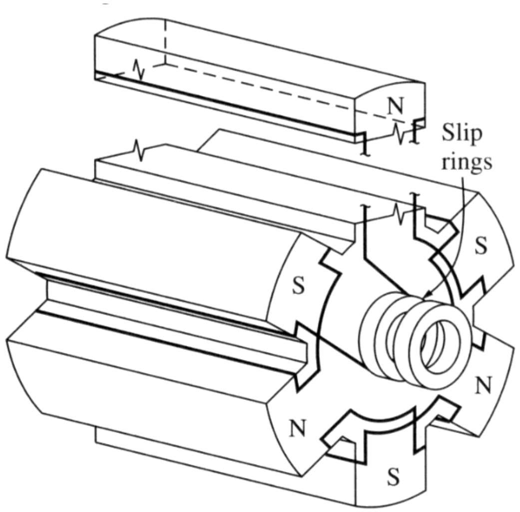
where f_s is the stator electrical frequency in Hz and n_m is the rotor mechanical speed in rpm and P is the number of poles (always an even number with 2 and 4 common)

- Round Rotor
  - Air-gap is constant, used with higher speed machines
- Salient Rotor (often called Salient Pole)
  - Air-gap varies circumferentially
  - Used with many pole, slower machines such as hydro

Synchronous Machine Rotors

- Rotors are essentially electromagnets





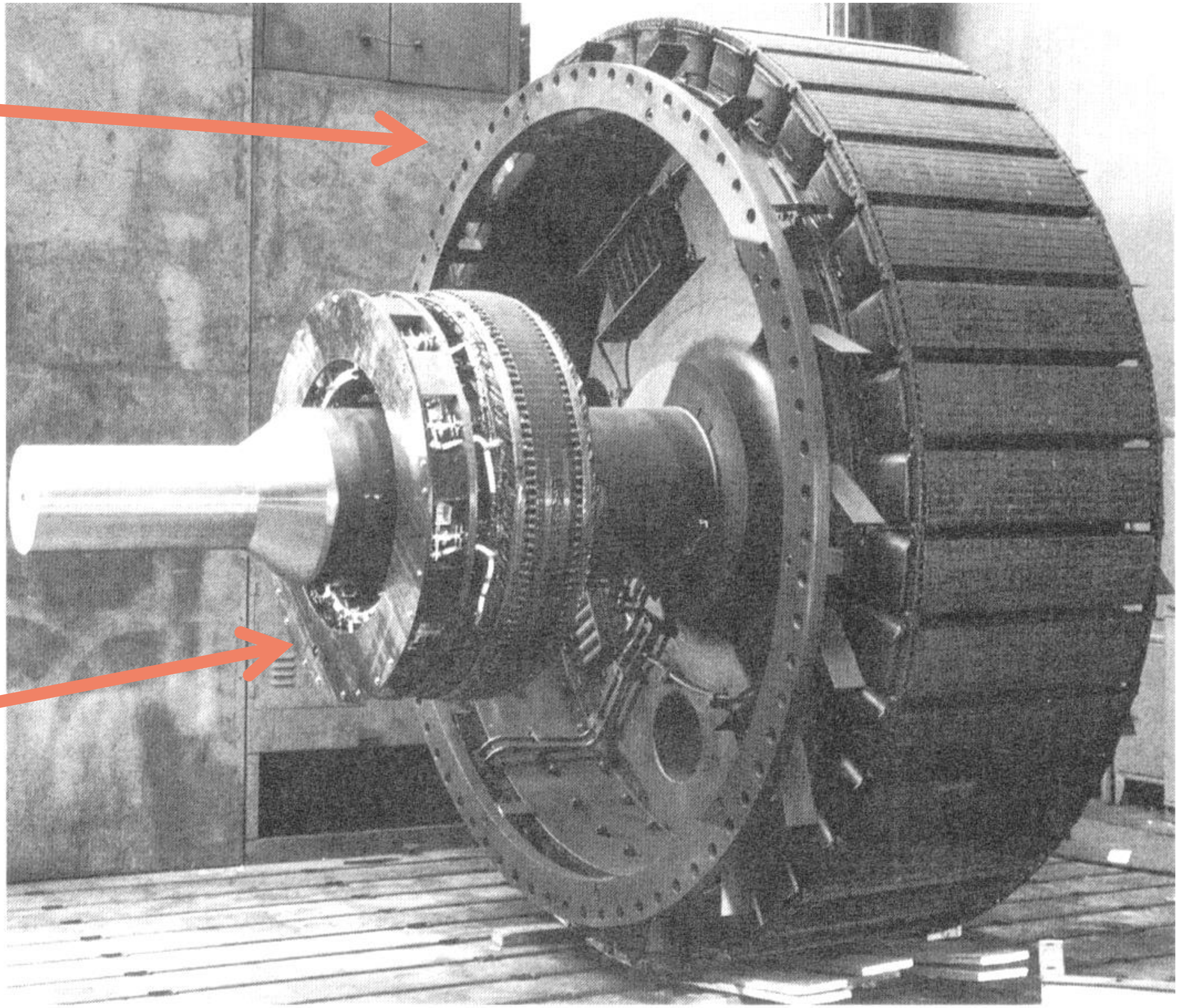
Two pole (P) round rotor

Six pole salient rotor

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

Synchronous Machine Rotors

High pole salient rotor

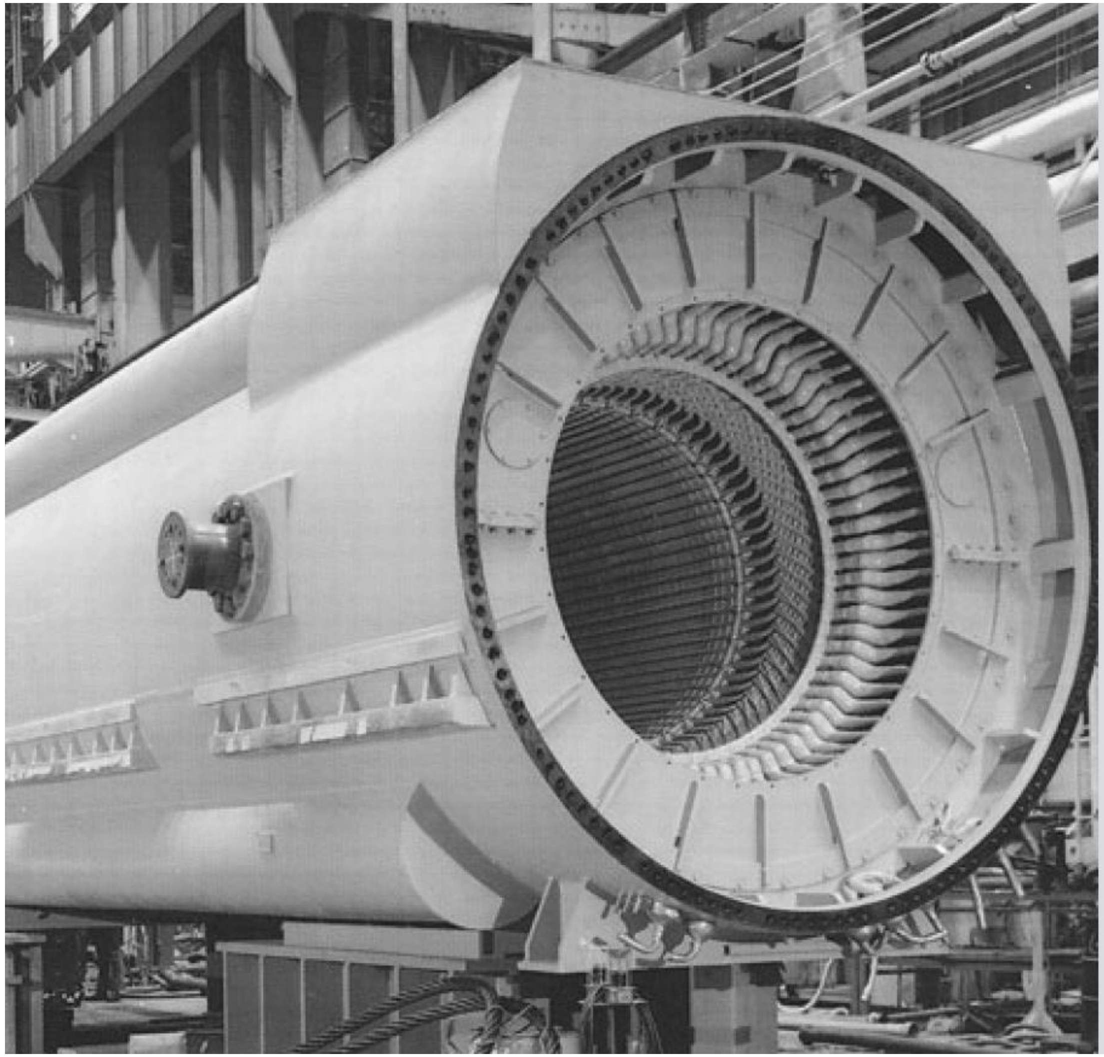


Shaft

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

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

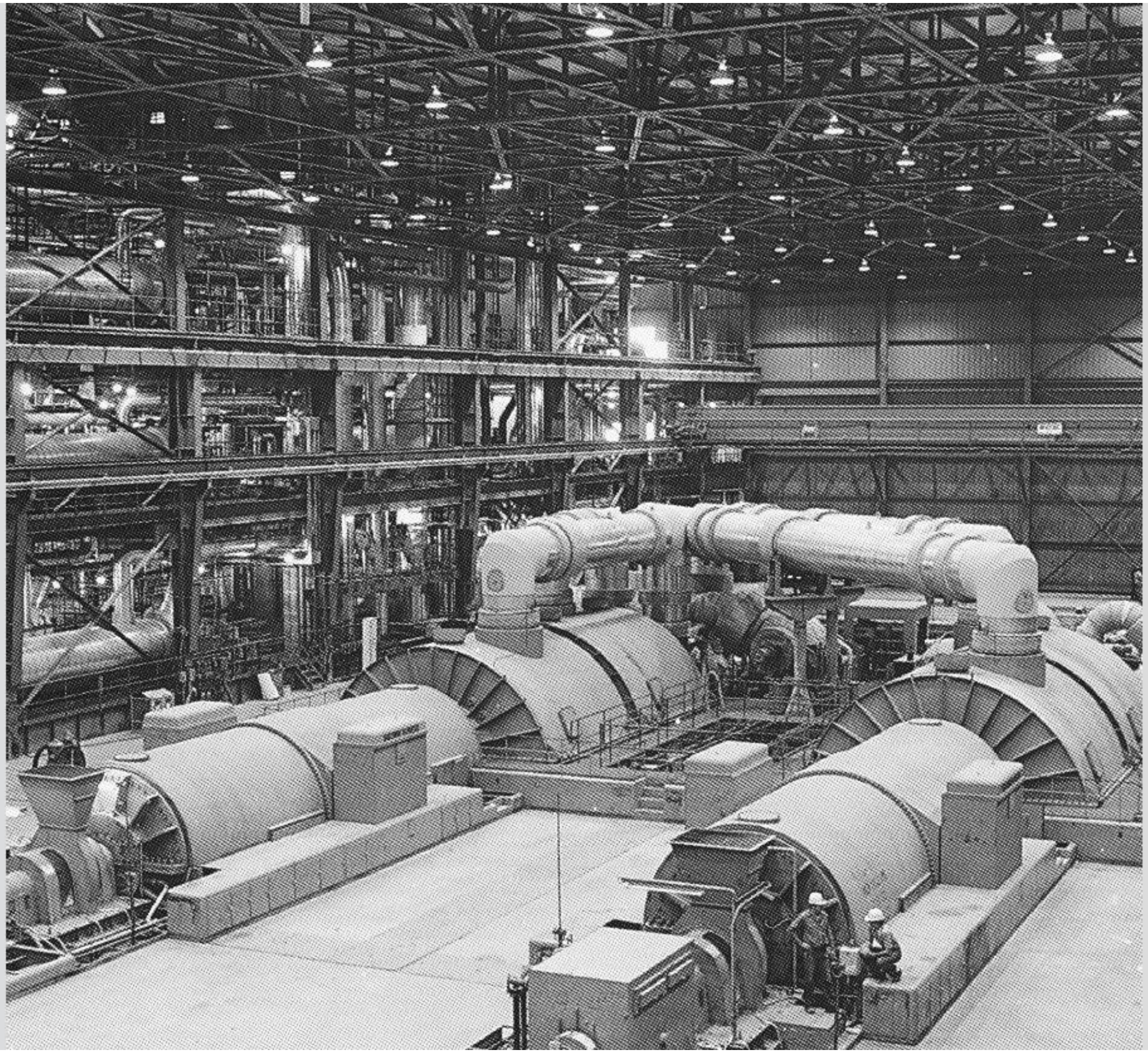
Synchronous Machine Stators



Generator stator showing completed windings for a 757-MVA, 3600-RPM, 60-Hz synchronous generator (Courtesy of General Electric.)

Image Source: Book, Beginning of Chapter 9 Photo

Synchronous Generators



1300-MW generating unit consisting of a cross-compound steam turbine and two 722-MVA synchronous generators (Courtesy of American Electric Power.)

Image Source: Book, Beginning of Chapter 12 Photo

Creating a Voltage in an Open-Circuited Generator

- With zero stator current, the only 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

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

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

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

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

Creating a Voltage in an Open-Circuited Generator

- Then by Faraday's law a voltage is induced

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

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

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

Creating a Voltage in an Open-Circuited Generator

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

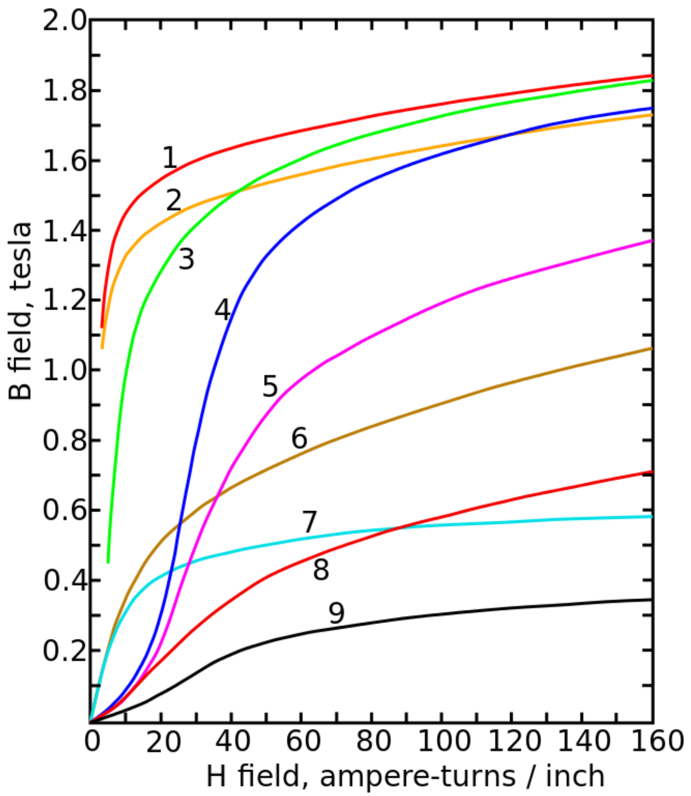
$$e_{aa'} = \frac{d\lambda_{aa'}}{dt} = -K I_f \omega \sin(\omega t + \theta_0)$$

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



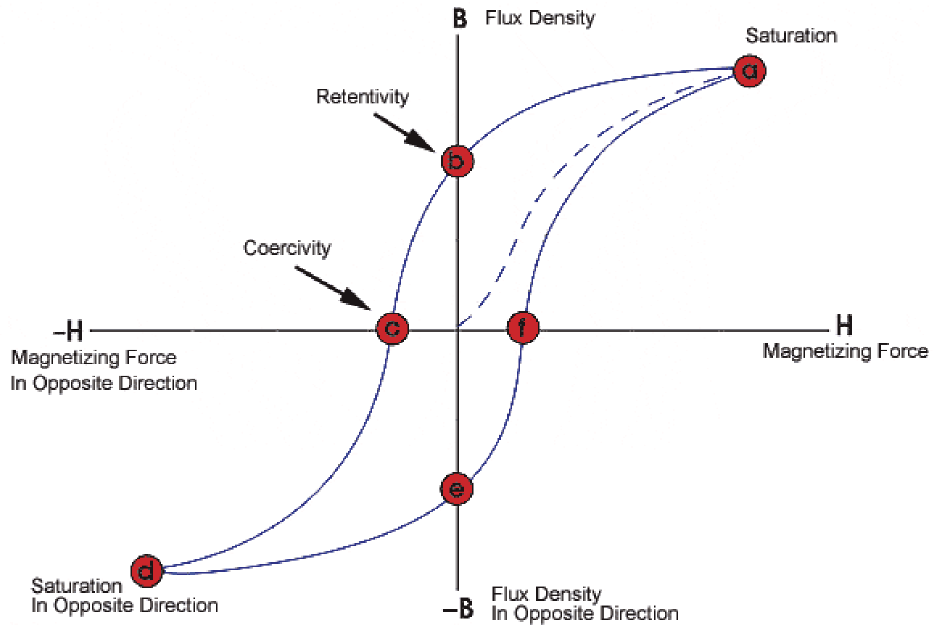
Magnetization curves of nine ferromagnetic materials, showing saturation. 1.Sheet steel, 2.Silicon steel, 3.Cast steel, 4.Tungsten steel, 5.Magnet steel, 6.Cast iron, 7.Nickel, 8.Cobalt, 9.Magnetite; highest saturation materials can get to around 2.2 or 2.3T

H is proportional to current

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

Magnetic Saturation and Hysteresis

- 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

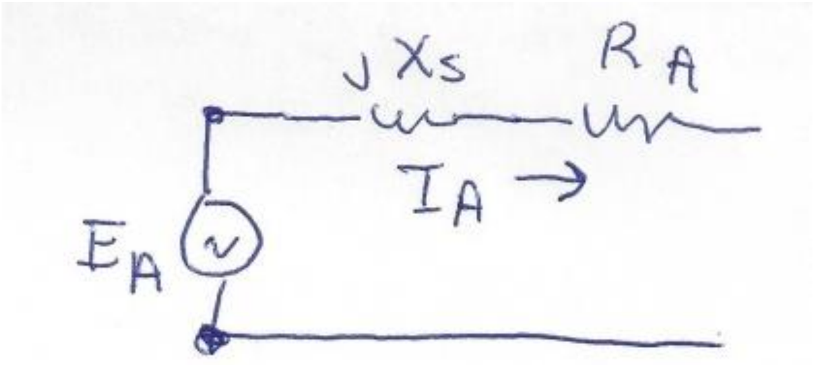
- When operating with an output current, the terminal voltage is not equal to the internally generated voltage
- This is due to several factors
  - Resistance in the stator windings
  - Self-inductance in the stator windings
  - Distortion of the air-gap magnetic field due to the stator current; that 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 classical 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



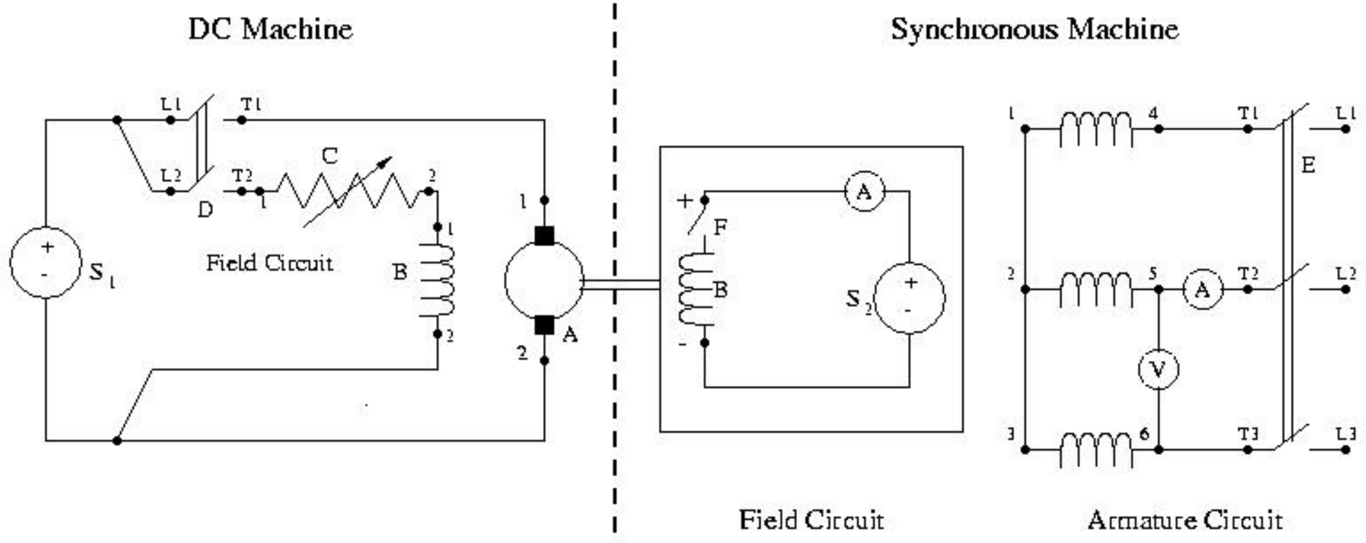
- As we've already covered this model is not particularly good for saturation and understanding the generator's dynamic response, hence the need for the more detailed models previously covered in Chapter 12

Synchronous Machine Testing to Determine Its Parameters

- These synchronous machine parameters can be determined from two tests (which you can do in optional Lab 3)
  - 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

Optional Lab 3 Setup

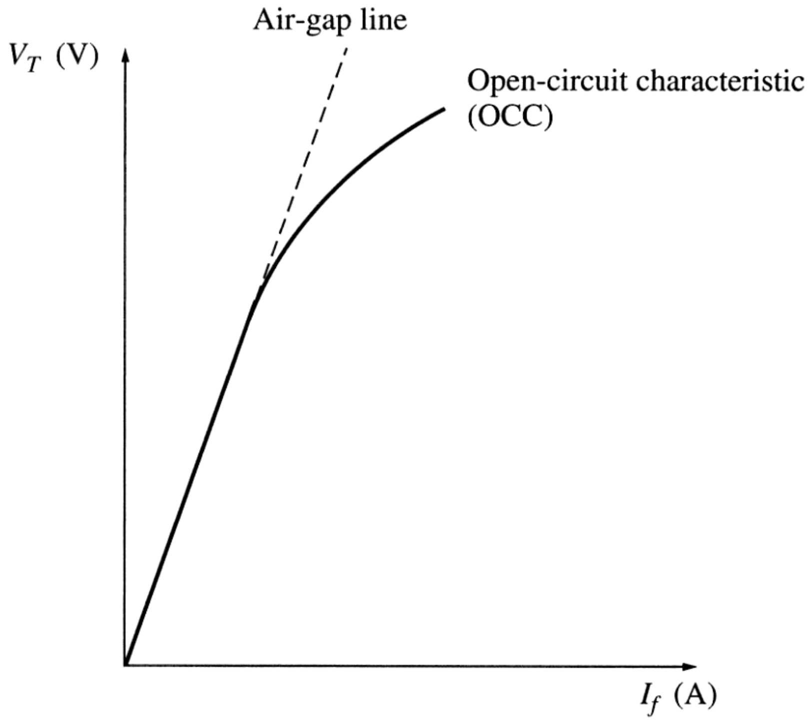
- You'll be using a dc machine (which is speed controllable) to drive a synchronous generator. In this lab you'll be doing open-circuit and short-circuit tests to determine its parameters



In the experiment you'll be measuring line-to-line values, which are sqrt(3) times the line-to-neutral values

Open-Circuit Characteristic (OCC)

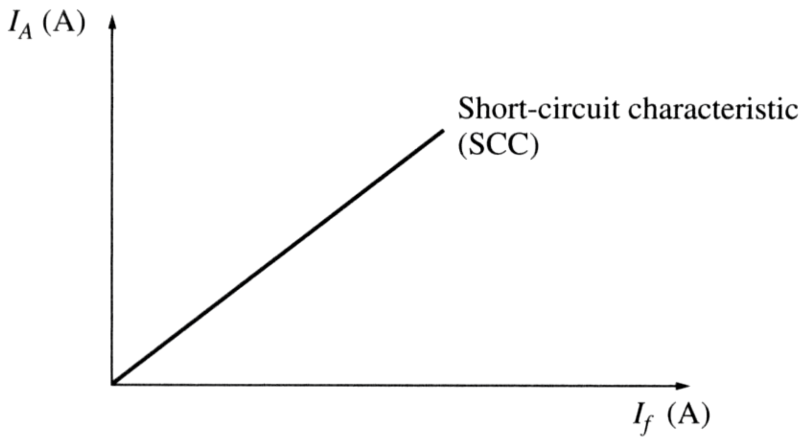
- The open-circuit characteristic (OCC) can be derived by gradually changing the field current when operating at a fixed frequency (e.g., synchronous speed)
  - Hysteresis needs to be considered when making field current adjustments
- Because there is no stator current, the internal voltage can be directly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

$$I_{A,SC} = \frac{E_A}{\sqrt{R_A^2 + X_S^2}} \qquad V_T = E_A - jX_s I_A$$



- Since usually $X_S >> R_A$, 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 E_A and of course the terminal voltage is now zero during the short-circuit.
- One approach is to approximate it as

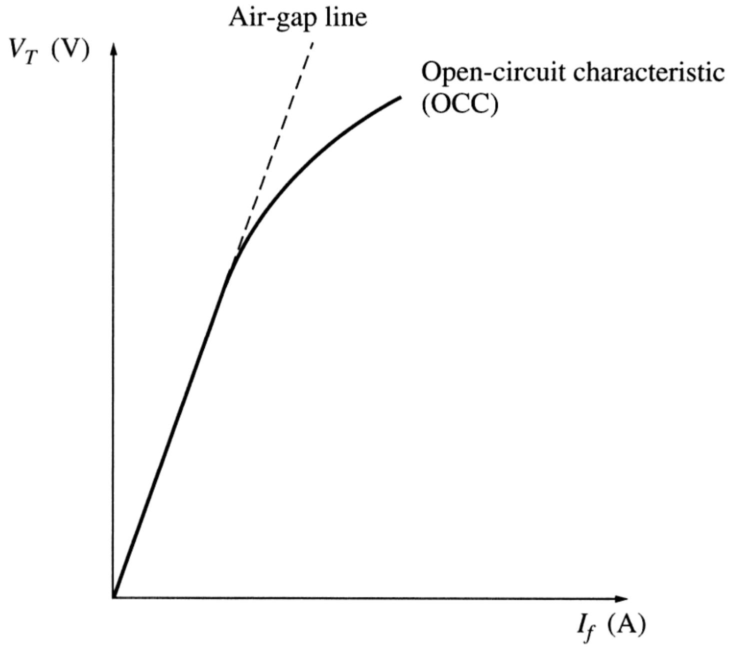
$$X_S \approx \frac{V_{OCC}}{I_{A,SC}}$$

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

Short-Circuit Test, cont.

- This approach is accurate up to the point of saturation. An alternative approach is to substitute the equivalent air-gap voltage instead of the V_{OCC} value.
  - This is commonly called the unsaturated synchronous reactance, X_u

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



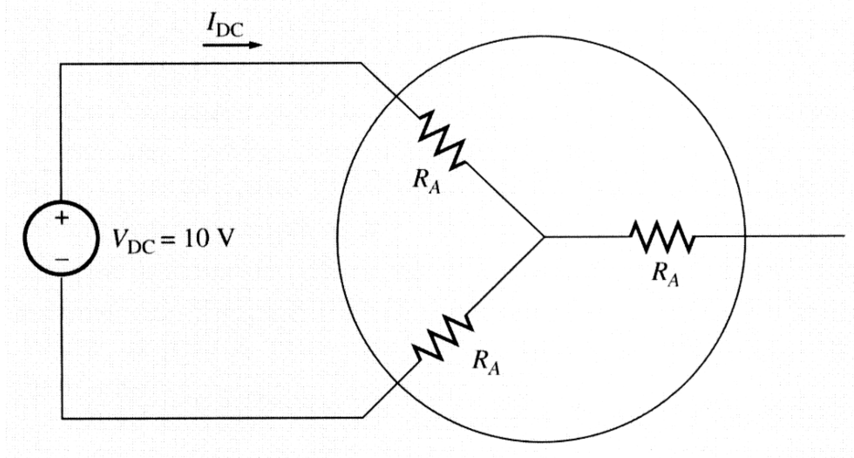
The amount of saturation depends on loading; in large generators saturation is explicitly modeled

Measuring R_A

- 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

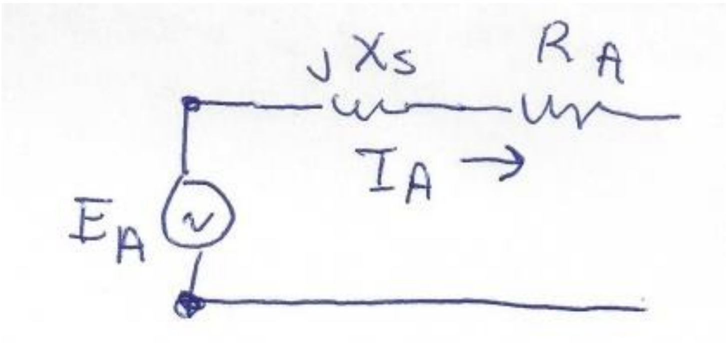
$$2R_A = \frac{V_{DC}}{I_{DC}}$$

- Or one could just use an ohmmeter



Operating Synchronous Machines Under Load 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
  - This is what we'll be assuming in later in the experiment
- How the voltage varies with loading is then given by



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

or

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

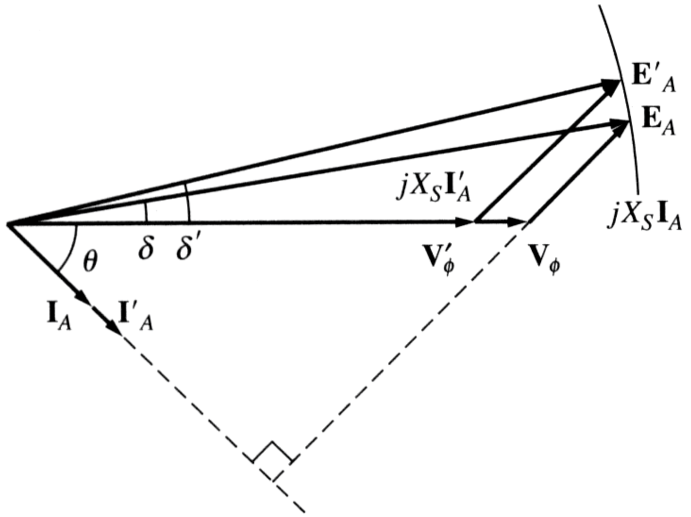
Operating Synchronous Machines Under Load with a Constant Field

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

$$V_T = E_A - jX_s I_A$$

  – Arbitrarily we can set the angle of V_T 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

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

$$P_{out,\text{pu}} = \frac{V_{T,pu} E_{A,pu}}{X_{s,pu}} \sin\delta$$

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

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

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

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

Quick Coverage of 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 V_f and field current is I_f
- Rotor (armature) currents are supplied through brushes and commutator

Types of DC Machines

- 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

Quick Coverage of DC Machines

- 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, ω_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, $V_T = V_F$ so

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

Renewable Resource Introduction and Modeling

- With the advent of more renewable generation in power systems worldwide it is important to have correct models
- Hydro systems have already been covered
- Solar thermal and geothermal are modeled similar to existing stream generation, so they are not covered here
- Coverage will focus on introducing wind and solar generation, along with their associated power flow and stability level models for wind and solar PV for integrated system studies
  - More detailed EMTP-level models may be needed for individual plant issues, like subsynchronous resonance
  - Models are evolving, with a desire by many to have as generic as possible models

Inverter-Based Resources (IBRs)

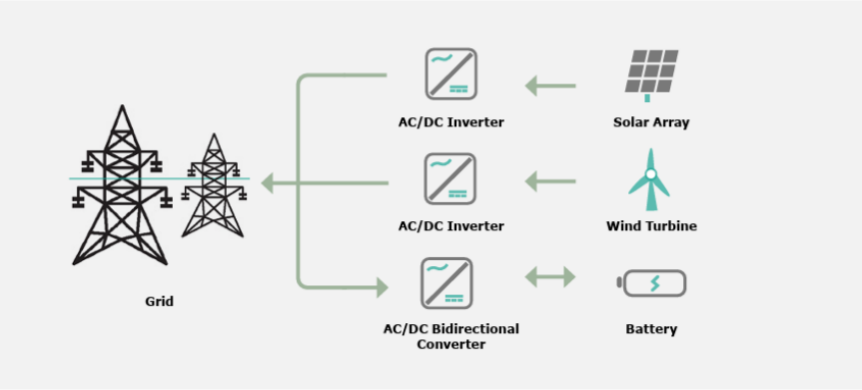
- The term inverter-based resources (IBRs) is used to refer to devices that connect to the power grid through an inverter
  - An inverter is a device that takes a dc input and converts it to ac at a specified frequency; a rectifier is the inverse of an inverter, dc to ac
- Inverters can produce or absorb reactive power, providing great flexibility; however, they are limited by their power rating
- IBRs are now widely used in the power grid to connect in wind turbines, solar photovoltaic arrays (pv), storage, and HVDC
- A short document describing IBRs is available from NERC at
  - www.nerc.com/pa/Documents/2023_NERC_Guide_Inverter-Based-Resources.pdf

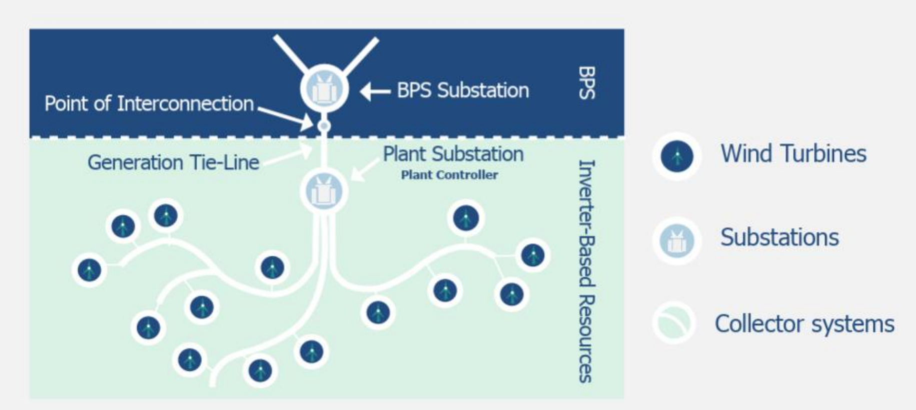
Differences between IBRs and Synchronous Generators

Differences between Inverter-Based Resources and Synchronous Generation	
Inverter-Based Resources	**Synchronous Generation**
• Driven by power electronics and software	• Driven by physical machine properties
• No (or little) inertia	• Large rotating inertia
• Very low fault current	• High fault current
• Sensitive power electronic switches	• Rugged equipment tolerant to extremes
• Very fast and flexible ramping	• Slower ramping
• Very fast frequency control	• Inherent inertial response
• Minimal plant auxiliary equipment prone to tripping	• Sensitive auxiliary plant equipment
• Dispatchable based on available power	• Fully dispatchable
• Can provide essential reliability services	• Can provide essential reliability services

What is an inverter?

An inverter is a power electronic device that converts direct current (dc) electricity to alternating current (ac) electricity.

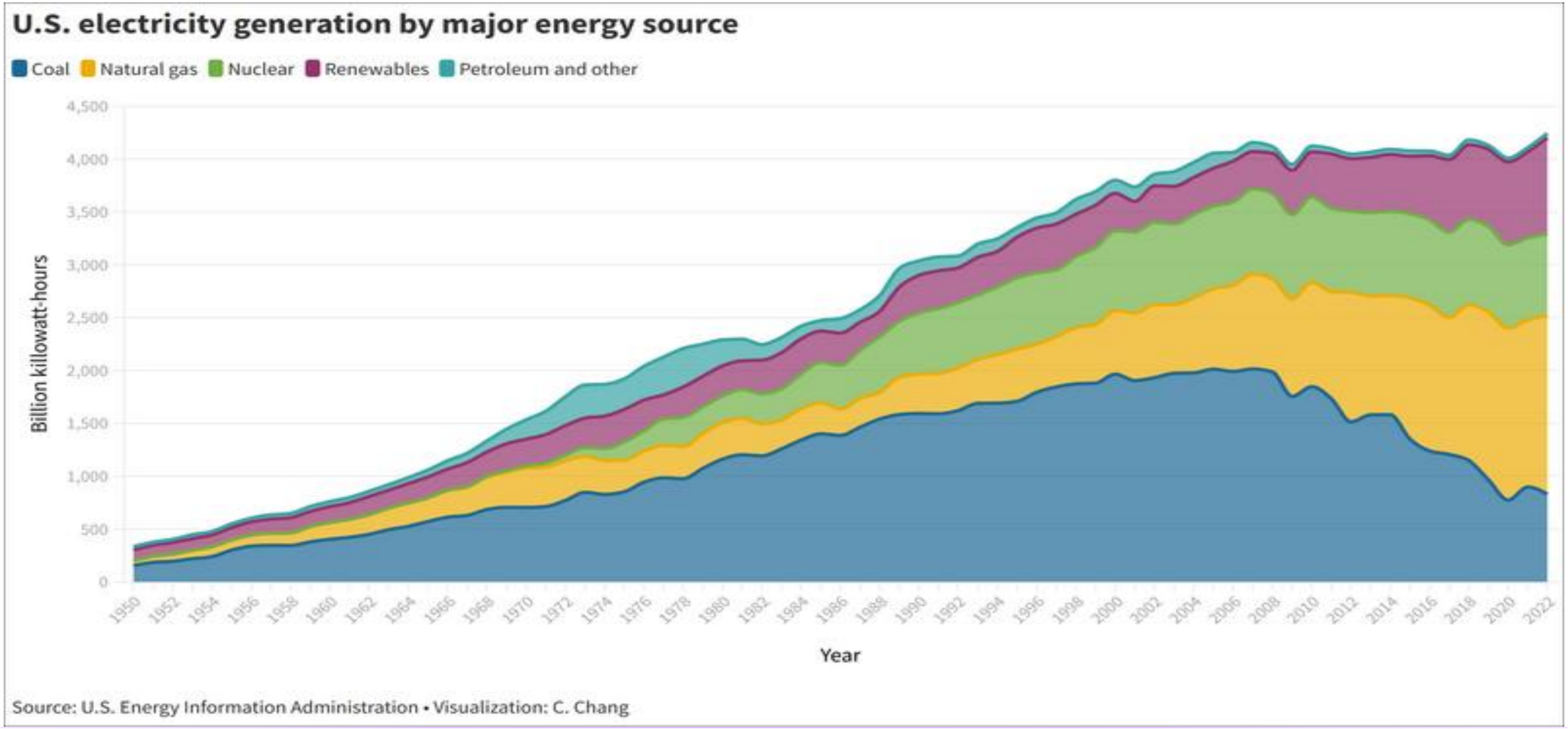




Images from www.nerc.com/pa/Documents/2023_NERC_Guide_Inverter-Based-Resources.pdf

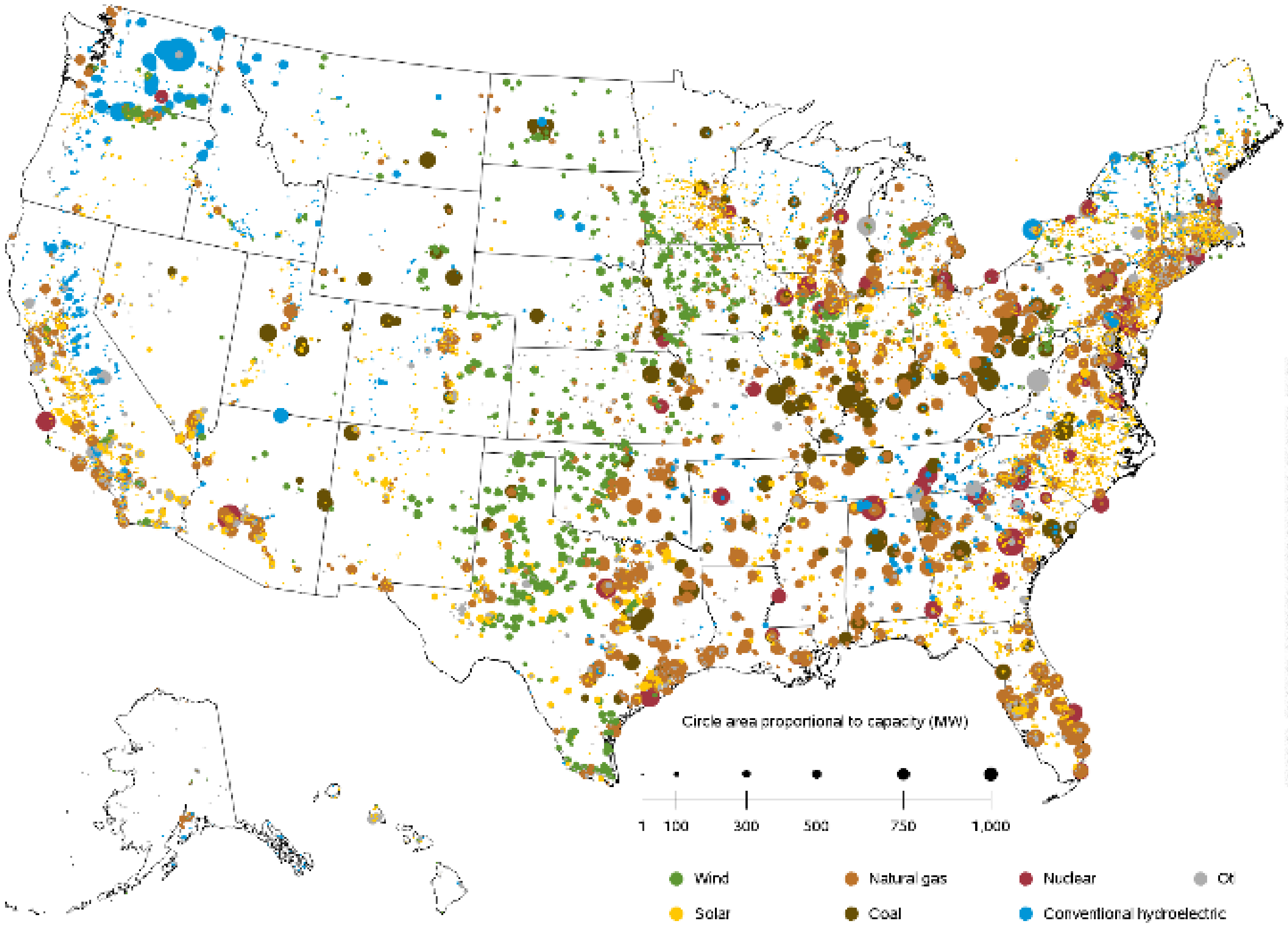
Changing Sources of Generation

- In the US and worldwide the sources of electricity are rapidly changing



Changing Sources of Generation, cont.

Operable utility-scale electric generating units, as of November 2024



Data sources: U.S. Energy Information Administration, Form EIA-860, 'Annual Electric Generator Report' and Form EIA-860M, 'Monthly Update to the Annual Electric Generator Report'

The sources variety substantially by state, the below image shows the change in the ERCOT (Texas) generation