Operating a Generator Paralleled to the Grid

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Introduction

- The steady state operation of a generator connected to a grid is different than when it is operating standalone
- Standalone
  - Voltage Regulator controls the voltage at the terminals
  - Speed Governor controls the frequency
- Paralleled to grid
  - Voltage Regulator controls the Reactive Power supplied by the generator
  - Speed Governor controls the Real Power supplied by the generator

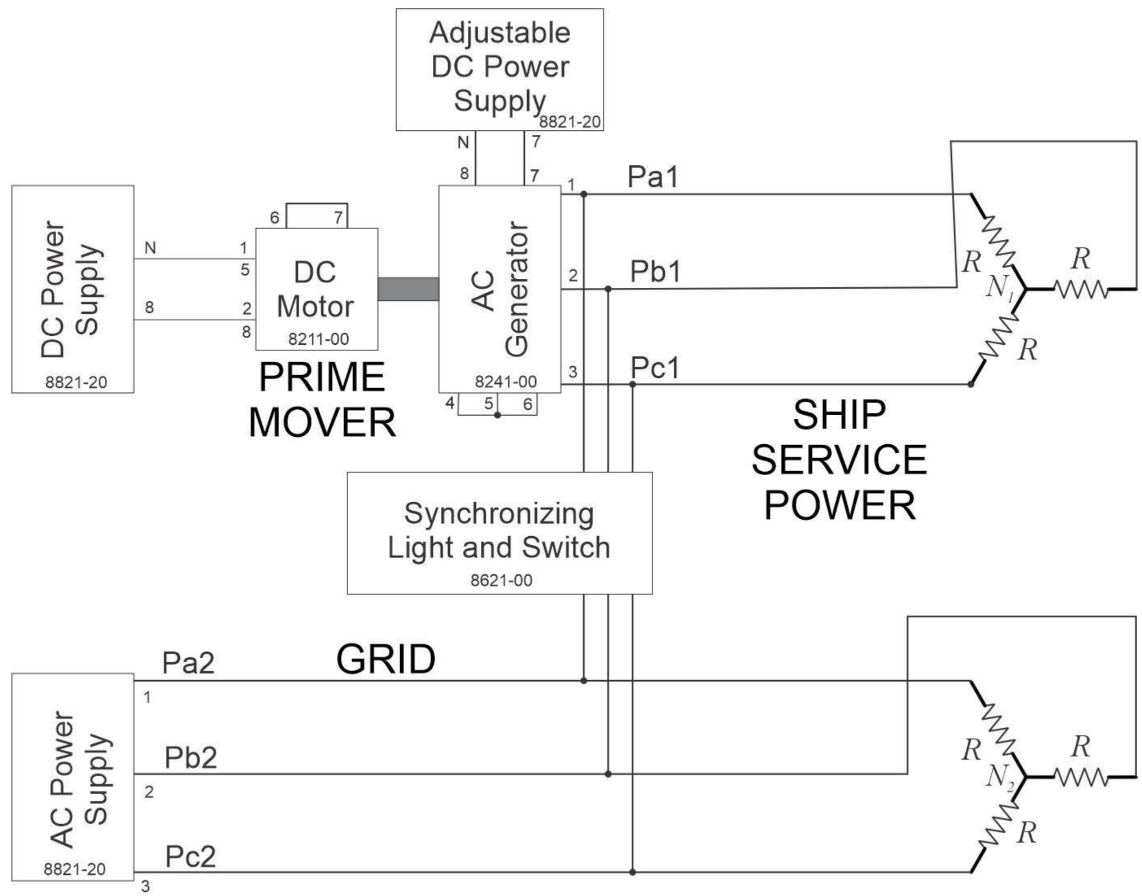
Purpose of this video

- Using a DC Motor to represent a prime mover and an AC synchronous generator ….
  - Demonstrate how field excitation on the DC motor and on the AC Generator control speed (Frequency) and voltage when the generator is not paralleled to the grid
  - Demonstrate how field excitation on the DC motor and on the AC Generator control Real and Reactive Power when the generator is paralleled to the grid.

Schematic

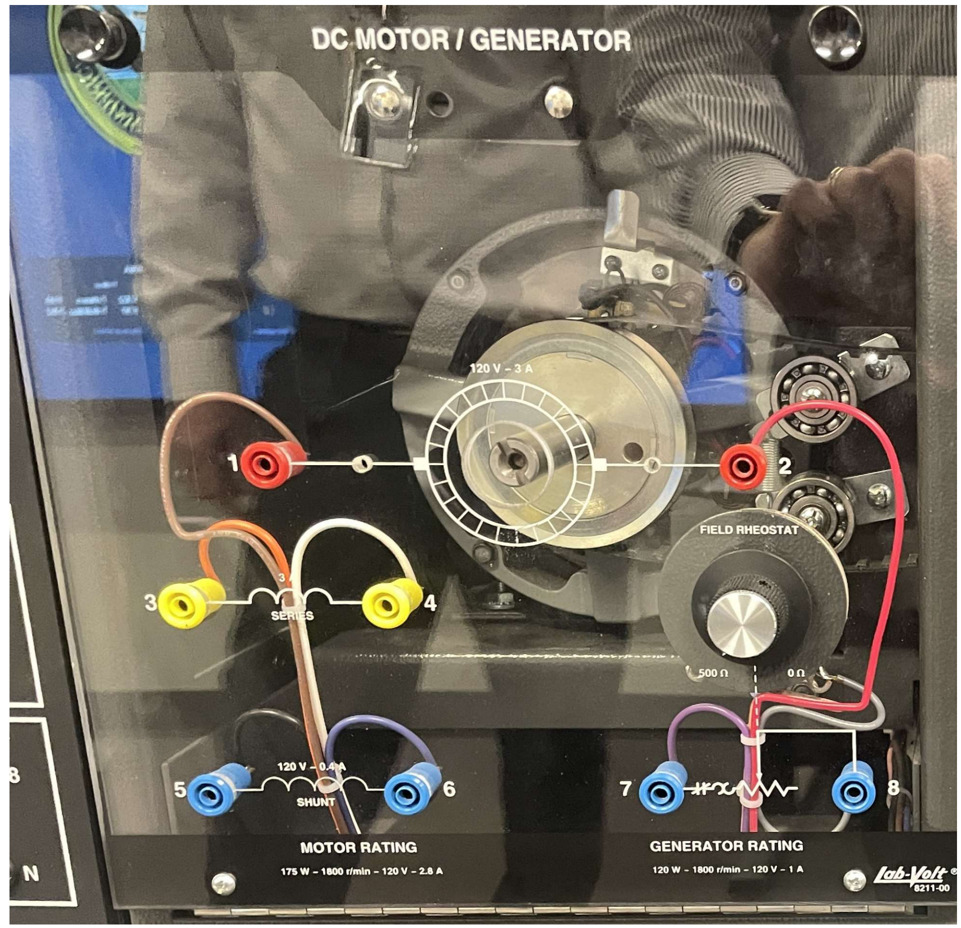
Power Meter
- Output of AC Generator

Voltage / Frequency Meters
- Output of AC Generator
- Output of AC Power Supply



Prime Mover

- Modeled by a DC motor
  - Constant DC Voltage applied to the Armature (Rotor) {1 and 2}
  - Field Rheostat controls current to the Shunt Winding on the stator (Field)
    - Shunt winding {5 and 6}
    - Field Rheostat {7 and 8}
    - Connected in series
      - DC voltage {5 and 8}
      - Series connection {6 and 7}



Steady State DC Motor Theory

$$V_a = K i_F \omega_m$$

Where ω_m is the angular speed of the motor shaft.

$$V_{DC} - V_a = i_a R_a$$

$$T = K i_F i_a$$

Where T is the Torque on the motor shaft.

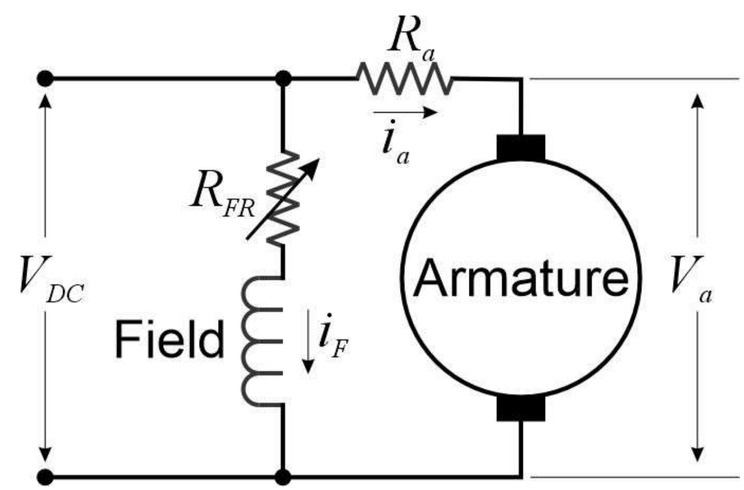
$$P = T\omega_m = V_a i_a = K i_F \omega_m i_a$$

$$P = K i_F \omega_m \frac{V_{DC} - K i_F \omega_m}{R_a}$$

For a given i_F, as power increases, ω_m decreases.

If P is fixed, then i_F controls ω_m

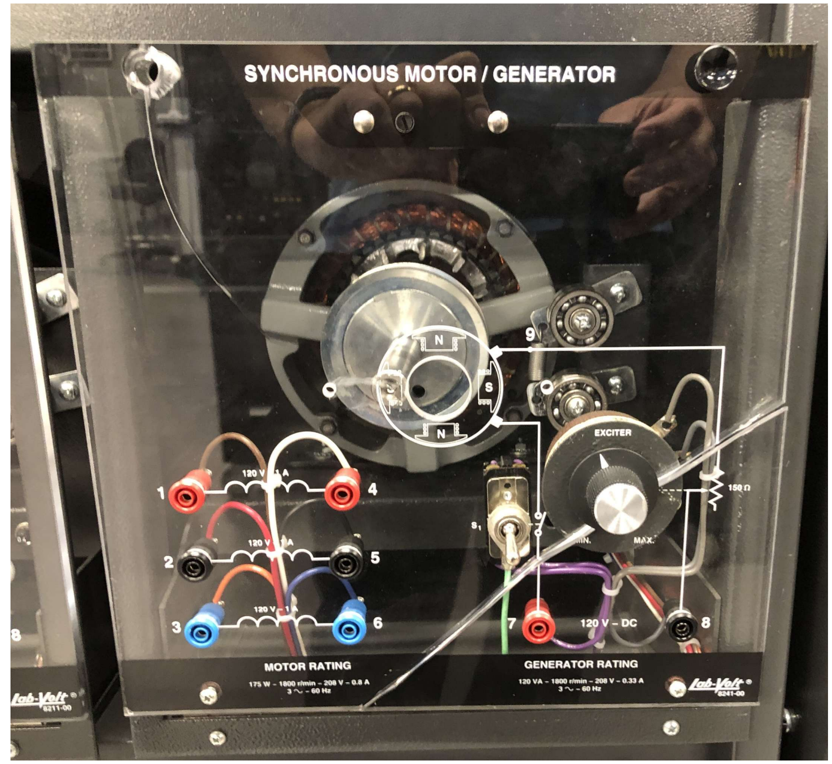
If ω_m is fixed, then i_F controls P



In a real prime mover
If P is fixed, the speed governor controls ω_m
If ω_m is fixed, then fuel throttle controls P

AC Generator

- Stator windings configured in "wye"
  - One end of each coil is connected together
  - Line to line voltage is $\sqrt{3}$ times the line to neutral voltage
  - Provides output power
- DC current in the field (rotor) winding controls the voltage on the stator windings when not paralleled
  - Current in the field winding is controlled by the exciter rheostat



Steady State AC Synchronous Generator Theory

$$E_{af} = K_{rs}\omega I_F$$

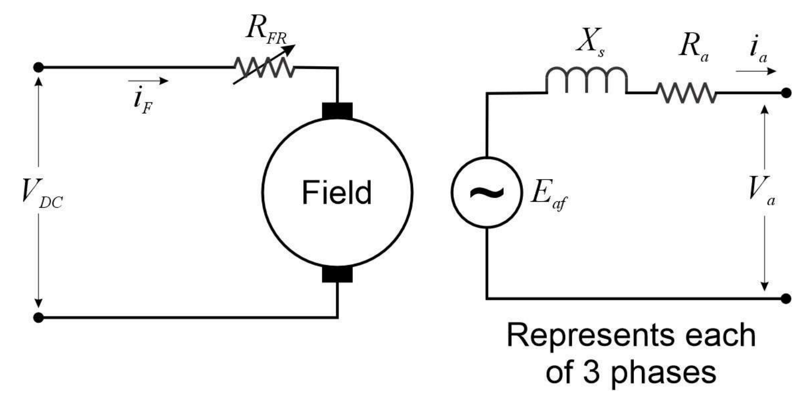
The electrical frequency ω is proportional to the mechanical frequency ω_m

The total Apparent Power for all three phases is given in phasor notation (using rms values)

$$S = 3\hat{V}_a \hat{\imath}_a^* = P + Q\hat{\jmath}$$

Neglecting the losses in R_a, the power on the shaft is simply P.

$$\hat{E}_{af} = X_s \hat{\imath}_a \hat{\jmath} + R_a \hat{\imath}_a + \hat{V}_a$$

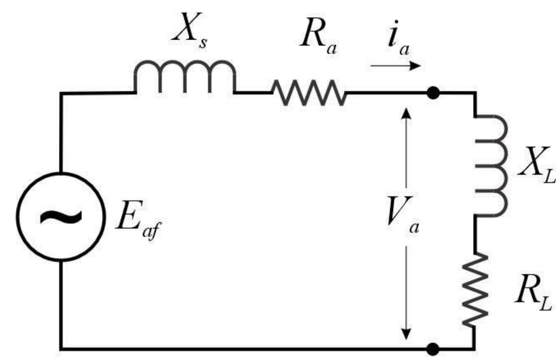


Steady State AC Synchronous Generator Theory – Not connected to the grid

$$\hat{E}_{af} = X_s \hat{\imath}_a \hat{\jmath} + R_a \hat{\imath}_a + \hat{V}_a$$

$$\hat{V}_a = X_L \hat{\imath}_a \hat{\jmath} + R_L \hat{\imath}_a$$

$$\hat{V}_a = \frac{X_L \hat{\jmath} + R_L}{(X_L + X_s)\hat{\jmath} + (R_L + R_a)} \hat{E}_{af}$$



Represents each of 3 phases

If the field excitation current and frequency stays constant, then as the load impedance decreases (Load apparent power increases), then the phase voltage also decreases. (Assumes shaft speed is regulated by the prime mover) Field excitation current I_F can be adjusted to maintain phase voltage.

$$E_{af} = K_{rs} \omega I_F$$

Steady State AC Synchronous Generator Theory – Connected to the grid

Angle (degrees)	Power Factor	(Power Factor)^-1
0	1.000	1.000
10	0.985	1.015
20	0.940	1.064
30	0.866	1.155
40	0.766	1.305
45	0.707	1.414

$$(R_a + X_S\hat{j})\hat{\imath}_a = E_{af} - v_a\angle\delta_a$$

$$(R_a + X_S\hat{j})\hat{\imath}_a = E_{af} - v_a\cos(\delta_a) - v_a\sin(\delta_a)\,\hat{j}$$

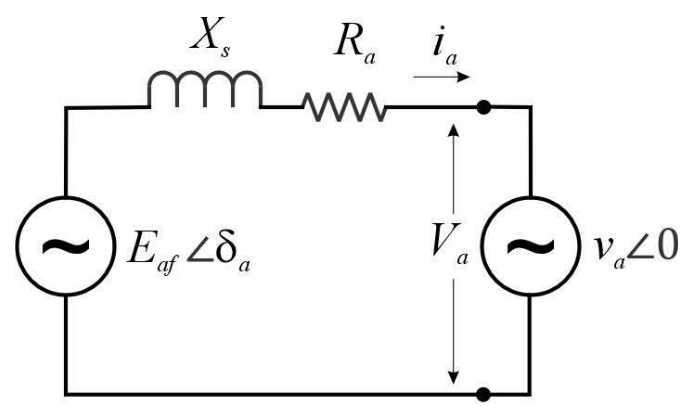
$$S = 3V_a i_a^* = P + Q\hat{j} = 3|V_a||i_a|\angle\theta$$

For P to be a constant, $|i_a|\cos(\theta)$ must be a constant (since $|V_a|$ is constant – grid voltage)

$$|i_a| \propto \frac{1}{\cos(\theta)}$$

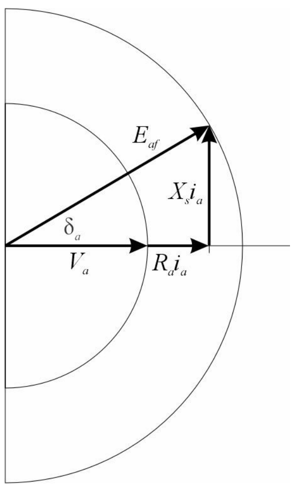
$$E_{af} = K_{rs}\omega I_F$$

E_{af} is controlled by I_F since ω is a constant

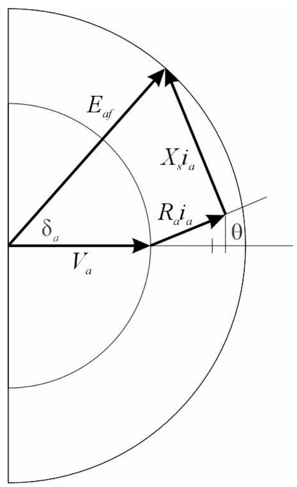


Represents each of 3 phases

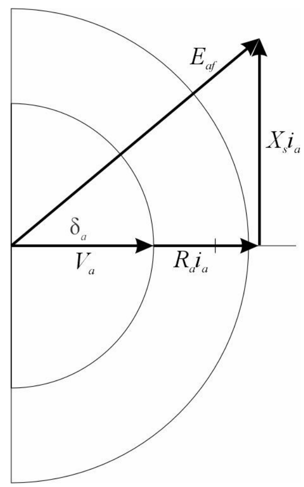
Steady State AC Synchronous Generator Theory – Connected to the grid



Baseline Case
Supplying
Unity Power Factor
(PF = 1.0)



Increased Excitation
on DC Motor
Same E_{af}
Power Increases
Power Factor supplies
Leading Loads



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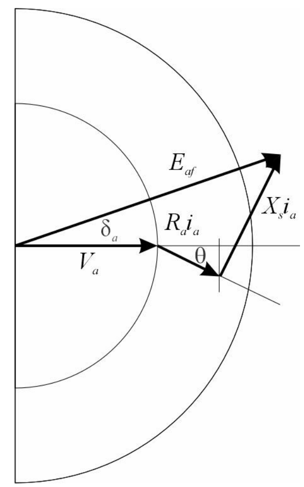
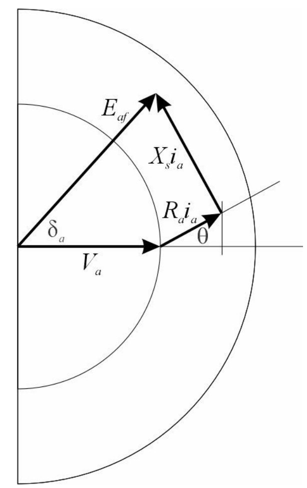


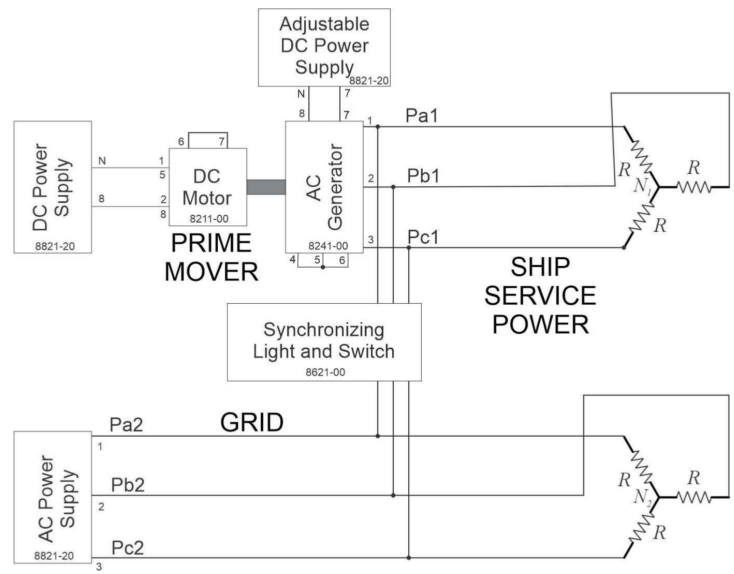
Baseline Excitation
on DC Motor
Increased E_{af}
Supplying
Lagging Loads



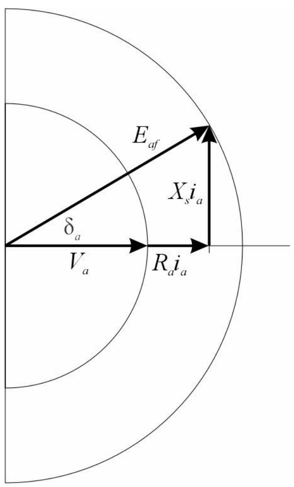
Baseline Excitation
on DC Motor
Decreased E_{af}
Supplying
Leading Loads

Procedure –Paralleled

- Parallel Generator to the Grid
  - Adjust Excitation on AC Generator to supply unity power factor
- Increase excitation on DC Motor
  - Measure Real and Reactive Power
- Adjust excitation on AC Generator to supply Unity Power Factor
  - Measure Real and Reactive Power
- Increase excitation on AC Generator
  - Measure Real and Reactive Power
- Decrease excitation on AC Generator
  - Measure Real and Reactive Power



Steady State AC Synchronous Generator Theory – Connected to the grid



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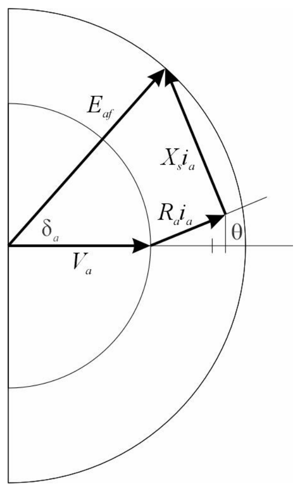

Increased Excitation
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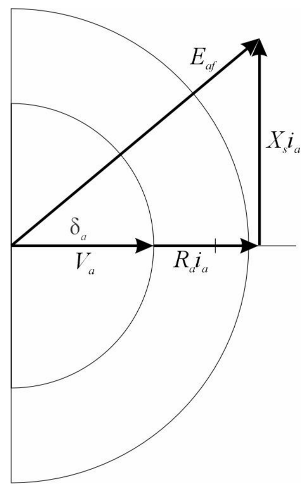
Same E_{af}
Power Increases
Power Factor supplies
Leading Loads



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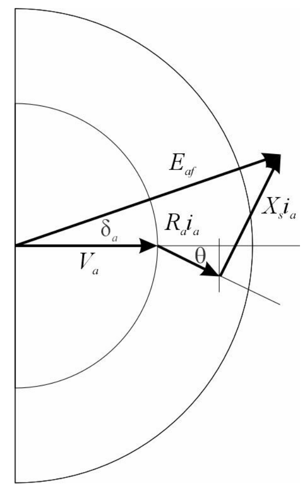
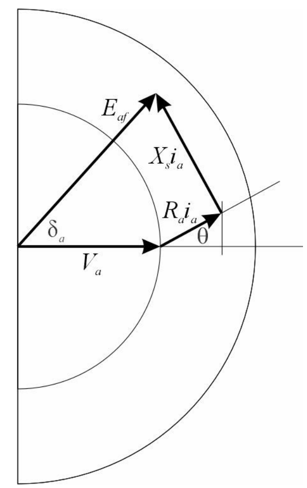


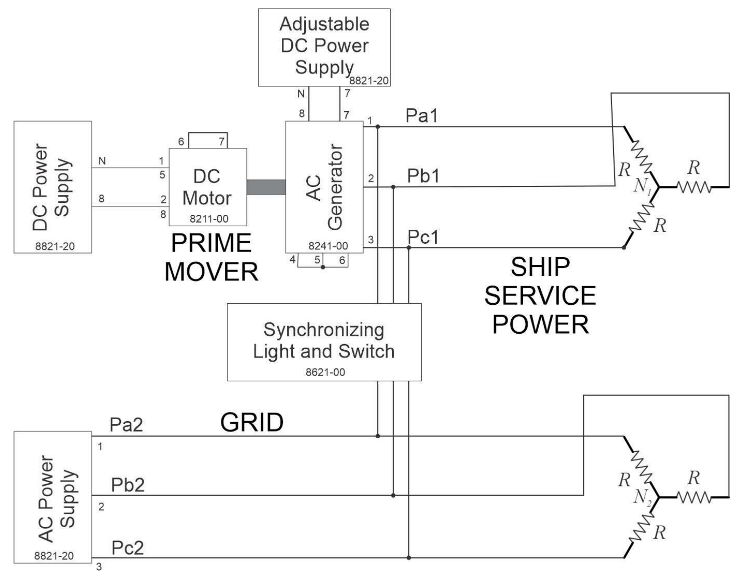
Baseline Excitation
on DC Motor
Increased E_{af}
Supplying
Lagging Loads



Baseline Excitation
on DC Motor
Decreased E_{af}
Supplying
Leading Loads

Procedure – Not Paralleled

- Adjust excitation to achieve 60 Hz and 208 volts line-to-line with 1200 ohm Load
  - Measure Real and Reactive Power (should be about 12 watts per phase)
- Turn on 300 and 1200 ohm resistors for the load
  - Measure Real and Reactive Power (should be less than 60 watts per phase)
  - Measure Frequency and voltage (should be less than 60 Hz, and 208 volts)
- Adjust DC motor field excitation to return to 60 Hz.
  - Measure Real and Reactive Power (should be closer to 60 watts per phase)
  - Measure Frequency and voltage (should be 60 Hz and closer to 208 volts)
- Adjust AC Generator field excitation to return to 208 volts line-to-line
  - Measure Real and Reactive Power (Should be closer to 60 watts per phase)
  - Measure Frequency and voltage (Should be a little less than 60 Hz and 208 volts)



Wrap Up