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Sandia National Laboratories

RCBC Electrical Generation

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Electrical Engineering SME

Sandia Industry Day

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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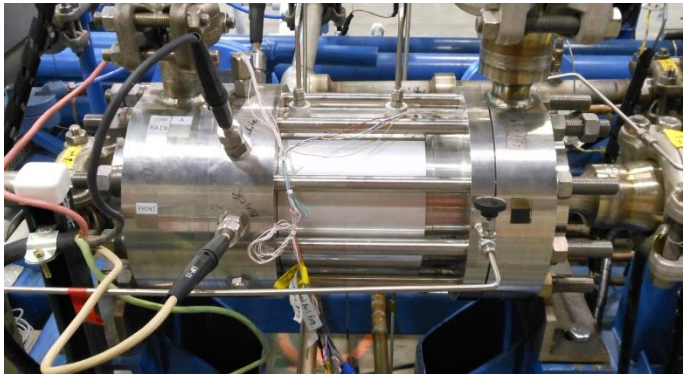
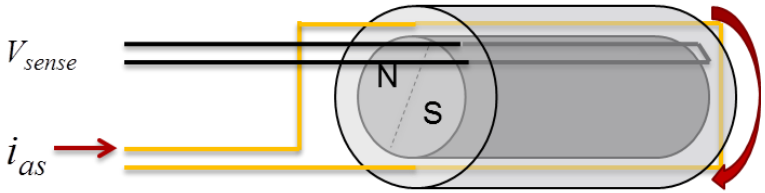
Overview: Motor/Generation Control

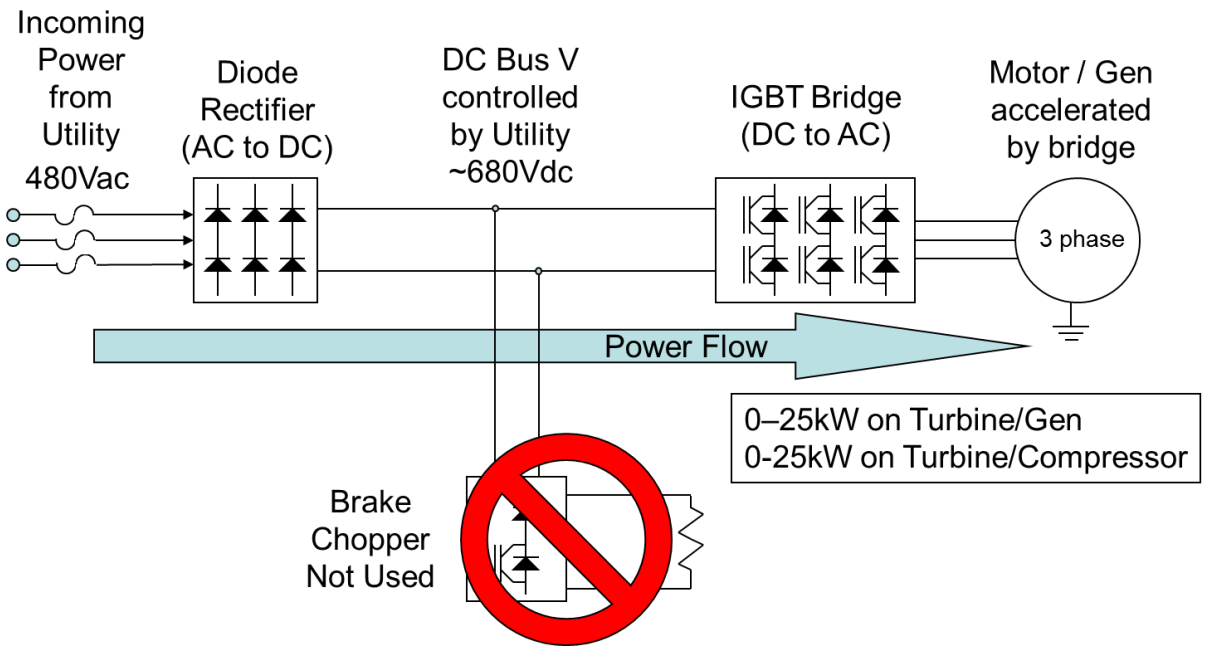
- Motor Controller Background
  - General Theory of Operation
  - Speed Control and Power Generation
- Machine Model Development and Predictions
  - Developing the model and Identifying Key Parameters
  - Steady State Model Performance Prediction
  - Dynamic Modeling
- Diagnosing and Solving Performance Issues
  - Evaluating Performance 'Symptoms'
  - Theory / Hypothesis of causes
  - Optical Encoder Solution





Motor Drive Provides Motoring and Generating Capability

- Utility Power is used for start-up and initialization (motoring)
- When system is “floating” no power is generated or consumed
- During generation
  - DC voltage rises and reverse biases the diode pack
  - Power is diverted from the DC bus to the DC dump load



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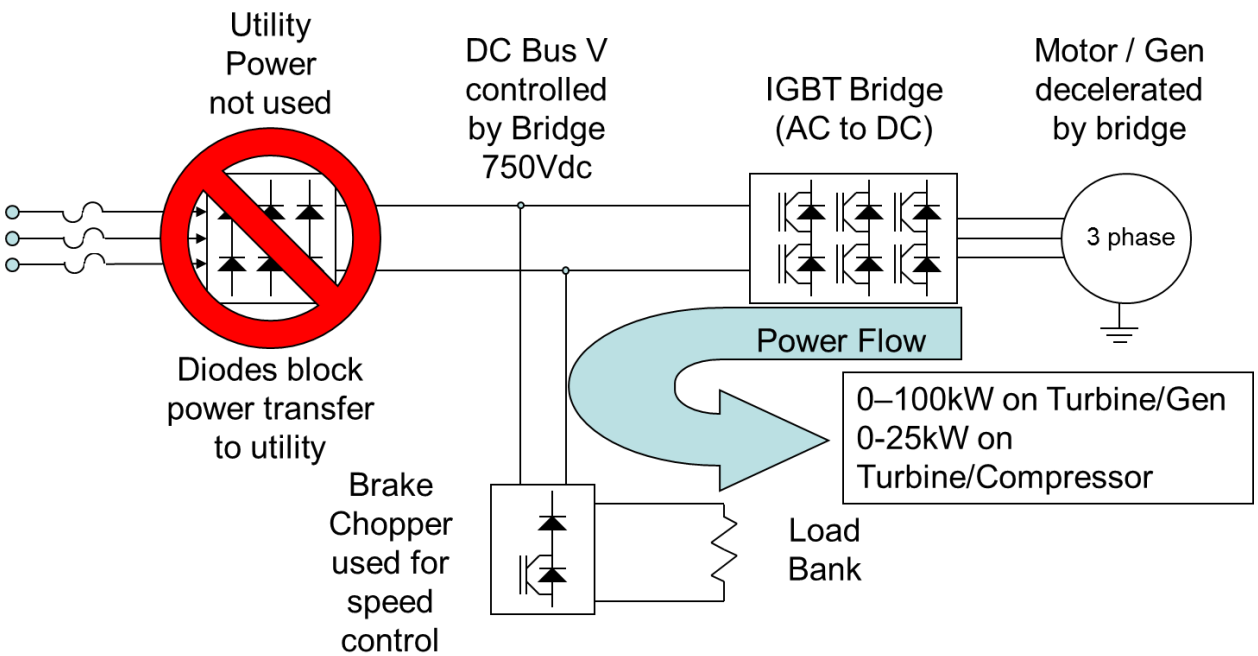
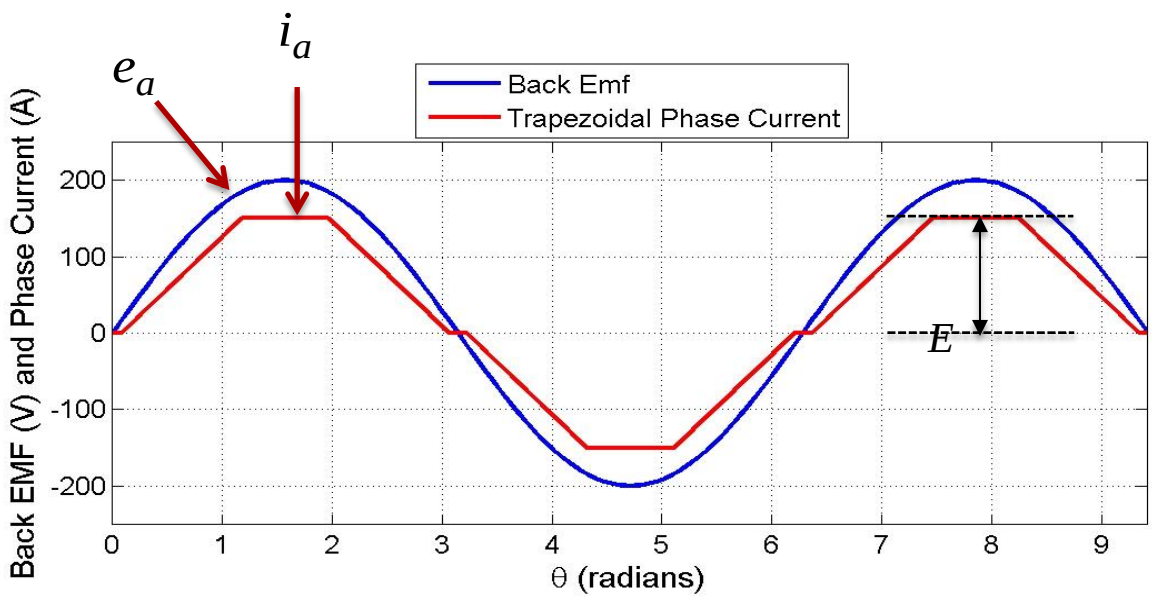


Power Generation Depends on Current Magnitude and Angle

- Power electronics regulate the generator phase currents
- Control Approach is termed "Trapezoidal Current Control" with the current aligned with the Back Emf
  - Currents are approximately sinusoidal
  - Phase angle between voltage and current is intended to be θ_{iv}=0

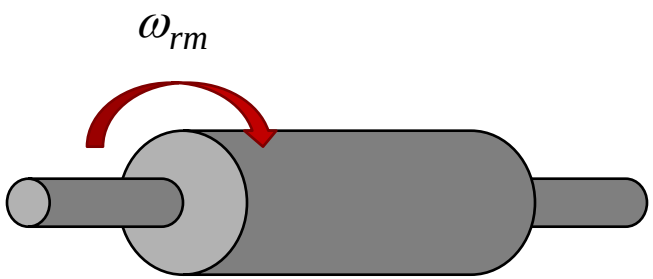


$$P_{elec} = i_a e_a + i_b e_b + i_c e_c$$

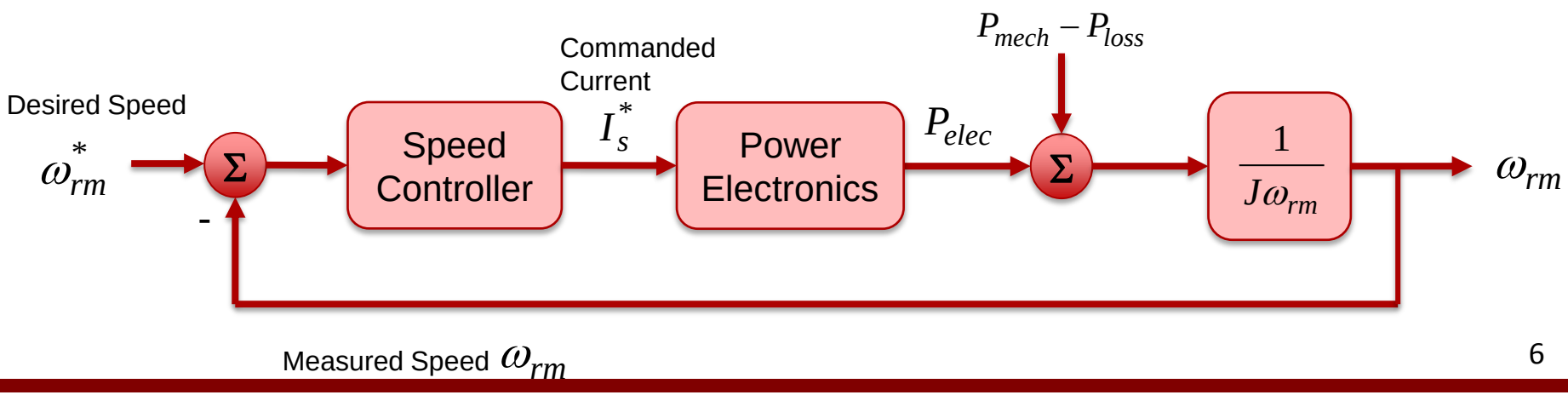
$$P_{elec} = \frac{3}{2} I_s E \cos(\theta_i - \theta_e)$$

Current Magnitude is Adjusted for Speed Control

- Desired Rotor Speed Is Fixed and Mechanical Power is Set
- Rotor speed is regulated through the control of electrical power extracted by the power electronics



$$\frac{d}{dt}\omega_{rm} = \frac{P_{elec} + P_{mech} - P_{loss}}{J\omega_{rm}}$$



A Machine Model was Developed to Predict Performance

- A lumped parameter state-variable machine model was developed
  - A transformation known as the 'Rotor Reference frame Transformation' is used
  - Laboratory tests, analysis and observation used to identify parameters in collaboration with *Knoll's Atomic Power Laboratory* and *Bettis Labora*

$$v_{qs}^{r} = r_s i_{qs}^{r} + \omega_r \lambda_{ds}^{r} + \frac{d}{dt}\lambda_{qs}^{r}$$

$$v_{ds}^{r} = r_s i_{ds}^{r} - \omega_r \lambda_{qs}^{r} + \frac{d}{dt}\lambda_{ds}^{r}$$

$$\lambda_{qs}^{r} = L_q i_{qs}^{r}$$

$$\lambda_{ds}^{r} = L_d i_{ds}^{r} + \lambda_m^{'r}$$

Model Parameters were Identified

- A lumped parameter state-variable machine model was developed
  - Open circuit measurements of phase-to-phase voltage allow calculation of flux linkage due to the permanent magnet
  - Stator resistance and inductance measured using LCR meter
  - Some assumptions made

$$v_{qs}^r = r_s i_{qs}^r + \omega_r \lambda_{ds}^r + \frac{d}{dt}\lambda_{qs}^r$$

$$v_{ds}^r = r_s i_{ds}^r - \omega_r \lambda_{qs}^r + \frac{d}{dt}\lambda_{ds}^r$$

$$\lambda_{qs}^r = L_q i_{qs}^r$$

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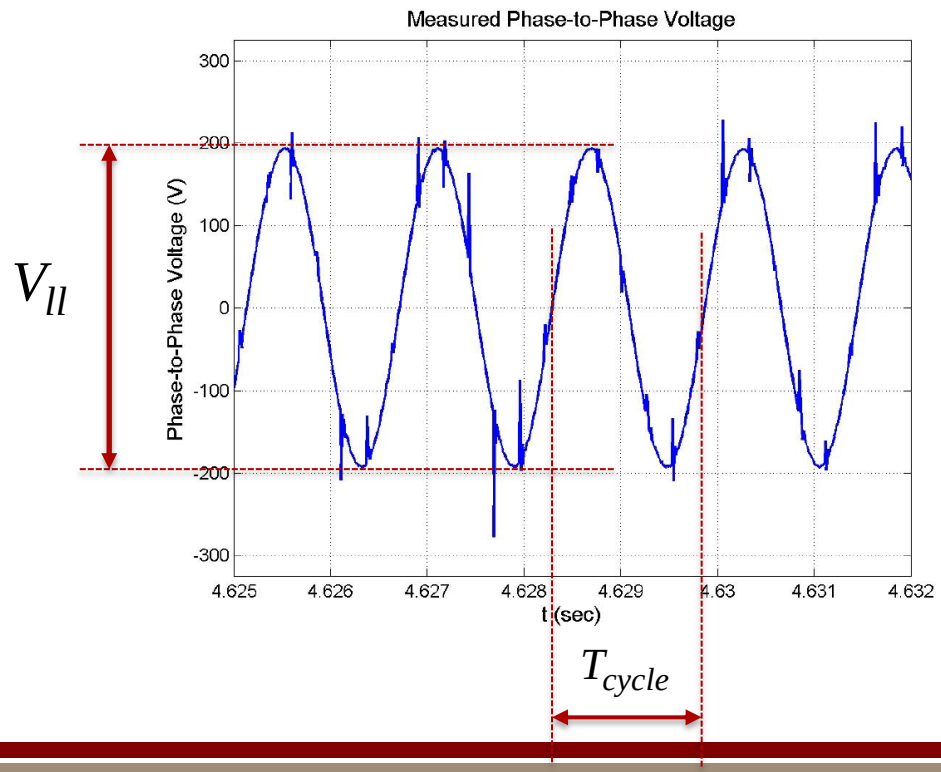
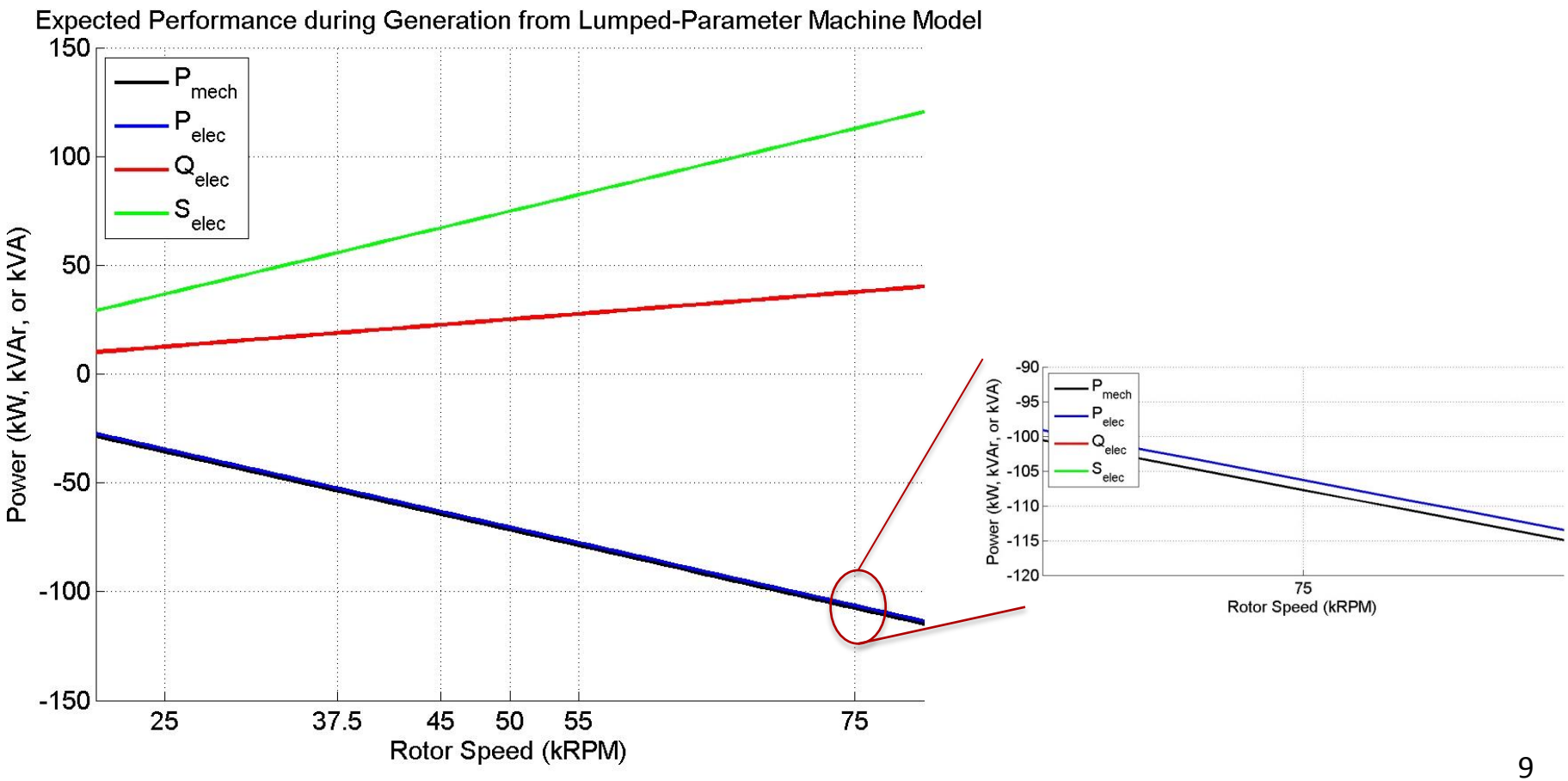


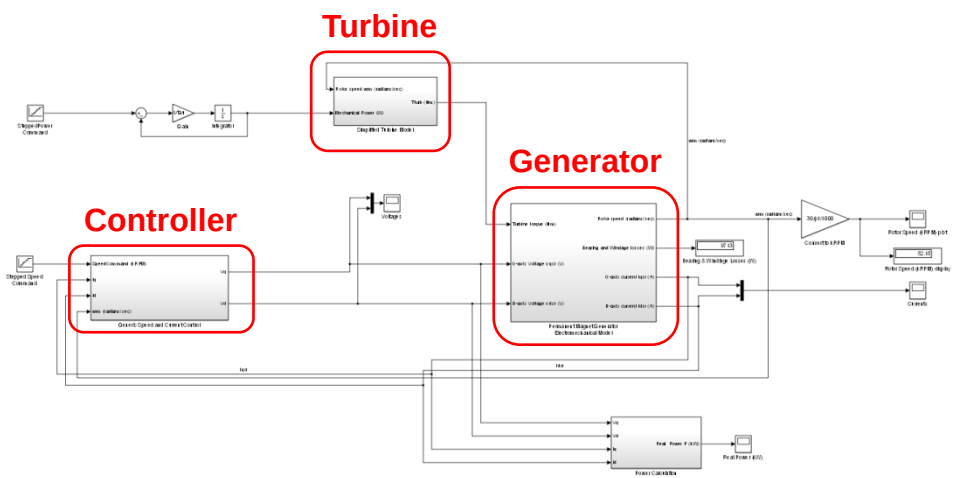
Steady-State Model Predicts Power Output

- At full current and 75 kRPM, model predicts >100 kW generation

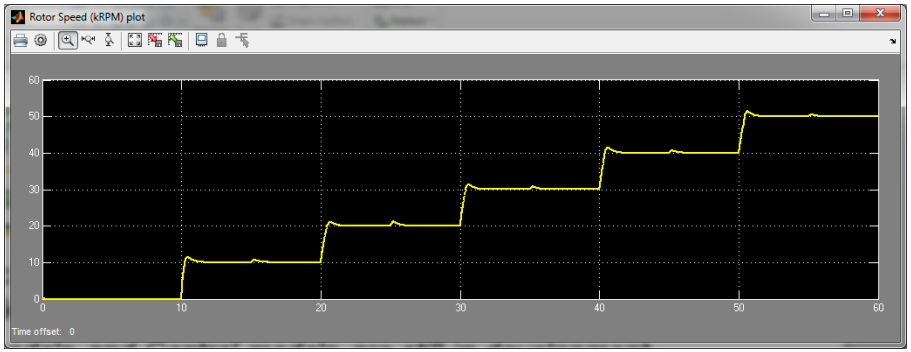


Dynamic Model Allows Simulation of Transient Response

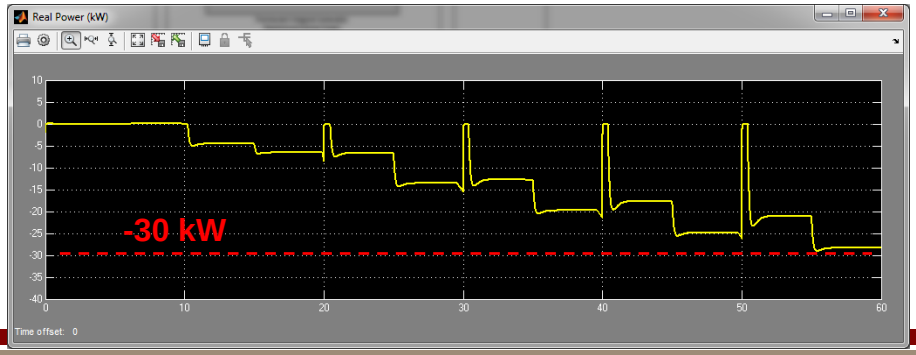
- A dynamic state-space model of the generator has been developed in Simulink
- Turbine and control models are still in development
  - Provides insights into transient response
  - Aids in control design



Speed (kRPM)



Electric Power (kW)



Several Performance Issues Have Caused Concern

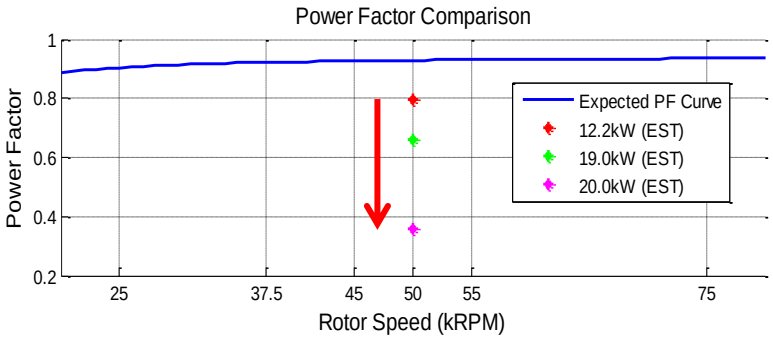
- Generator Control tends to shut-down for power levels between 20kW-30kW
  - Low Power Factor
  - Excessive Current
  - Large Voltage Spikes
  - Generator voltage depression
  - “Instability” in the generator control

- Each of these symptoms may be attributed to error in the rotor angle sensor

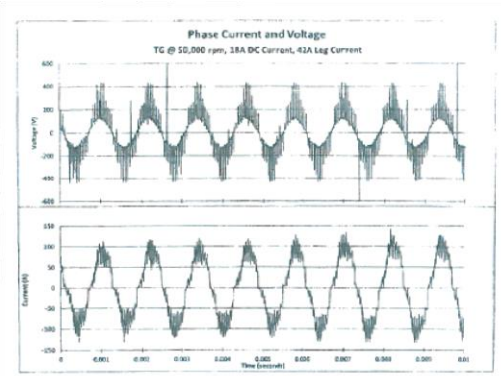
Low Power Factor is Directly Caused by Error in Rotor Angle Measurement

- Electrical Power: $$P_{elec} = \frac{3}{2} I_s E \cos(\theta_i - \theta_e) = \frac{3}{2} I_s V_s \underbrace{\cos(\theta_i - \theta_v)}_{\text{Power Factor}}$$

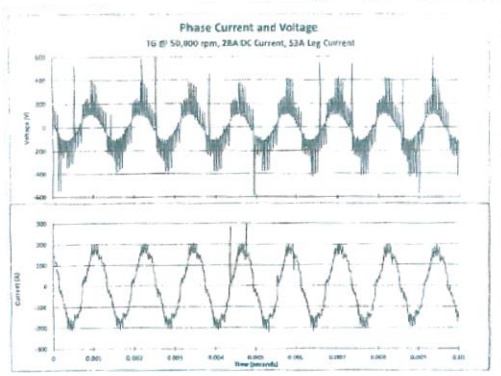
- The model indicates a high power factor (over 0.90). Testing, however, indicates that machine power factor degrades as power goes up.



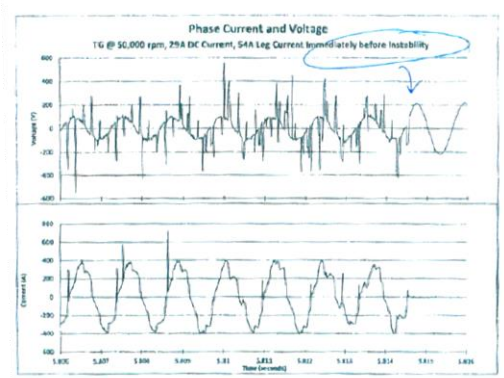
$P = 12.2\,\text{kW},\ S \approx 15.3\,\text{kVA}$



$P = 19\,\text{kW},\ S \approx 28.9\,\text{kVA}$

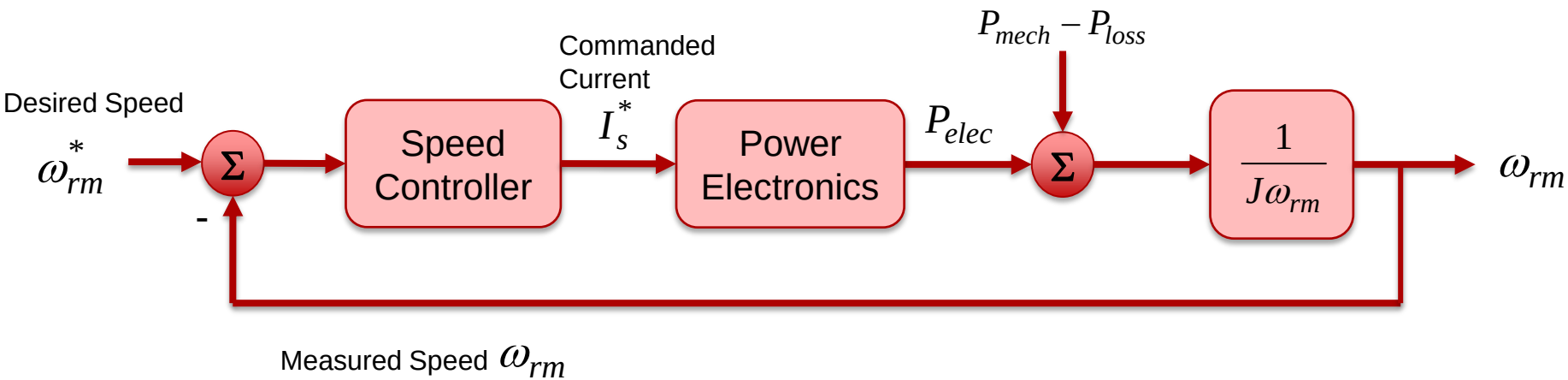


$P = 20\,\text{kW},\ S \approx 56.3\,\text{kVA}$



Excessive Current is Caused by Controller Response to Drop in Power

- As $(\theta_i - \theta_e)$ increases, $\cos(\theta_i - \theta_e)$ decreases and thus P_{elec} decreases
- Commanded Current I^* is increased by the controller to compensate



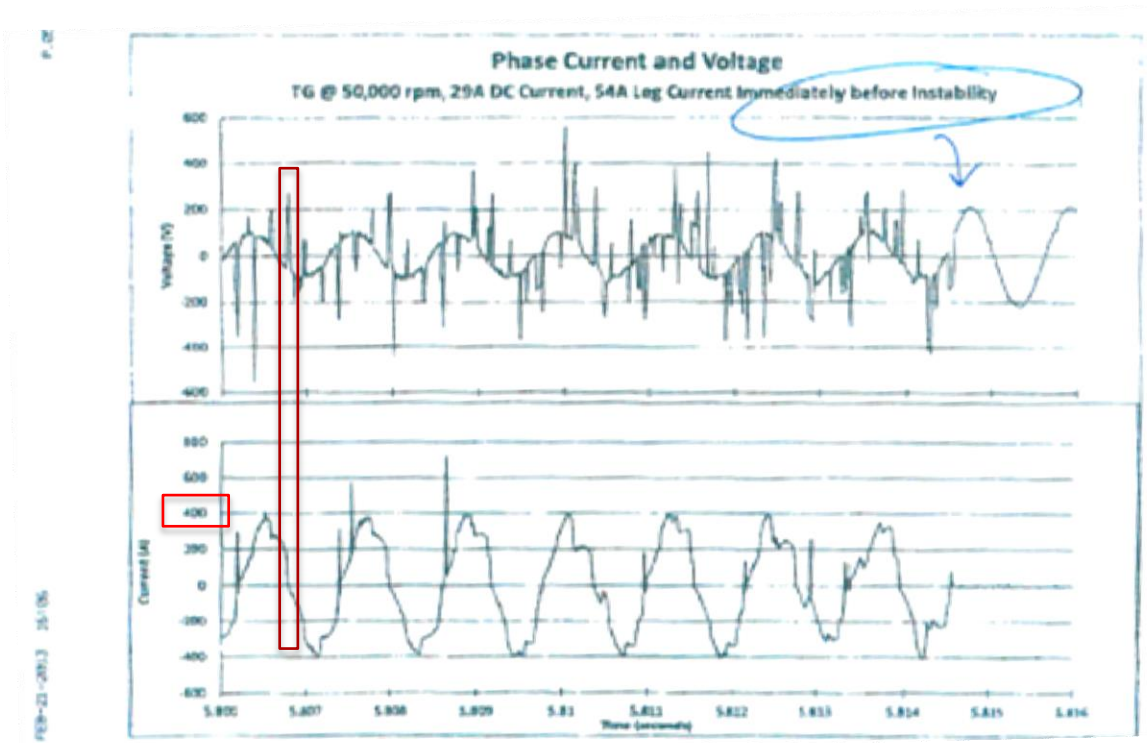
$$P_{elec} = \frac{3}{2} I_s E \cos(\theta_i - \theta_e)$$

Voltage Spikes are Caused by Inductor Saturation

- As rotor angle error grows, current magnitude grows to compensate
- As phase current grows, inductor currents go in and out of saturation, causing voltage spikes.

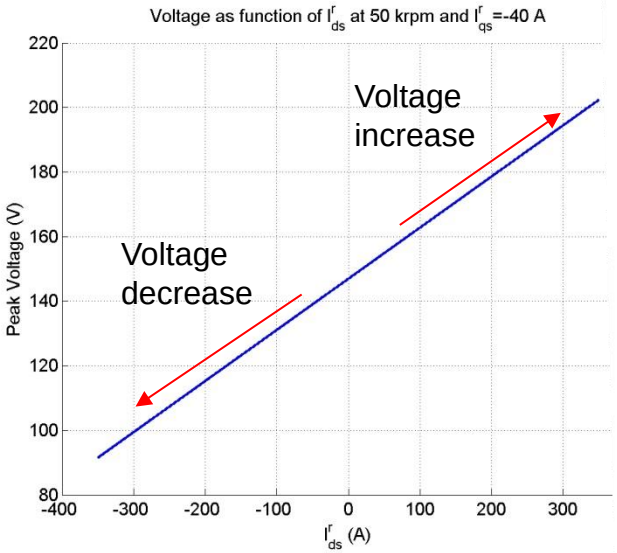
$$v = \Delta L \frac{di}{dt} + i \frac{d\Delta L}{dt}$$

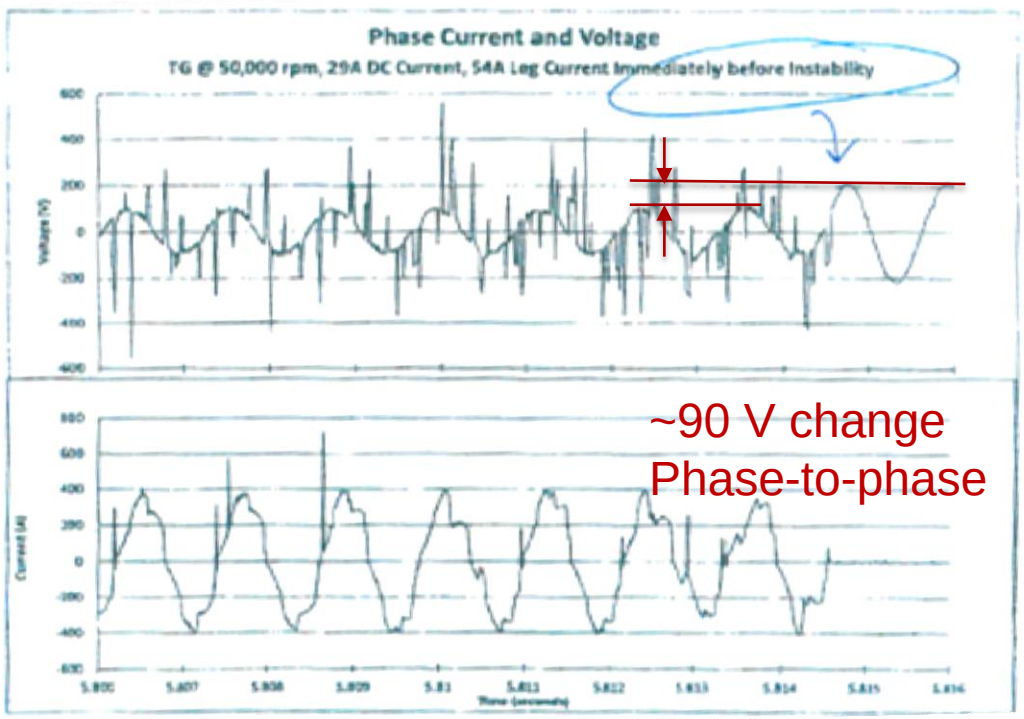
Currents reach 400 A !



Experimental Evidence of Rotor Angle Measurement

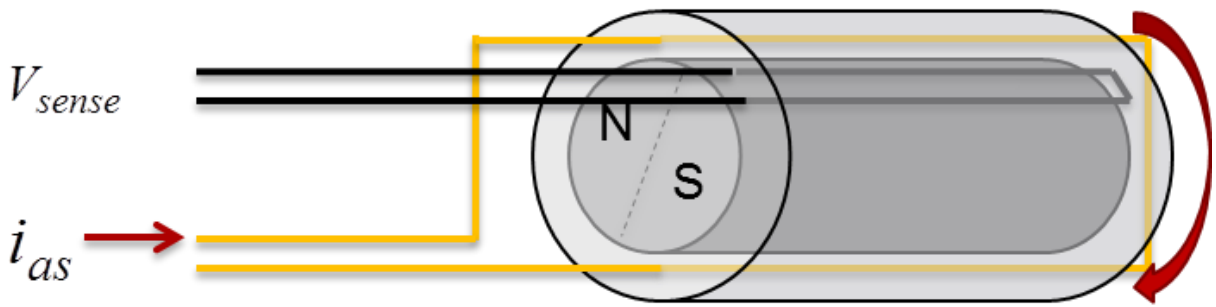
- Large phase currents result in reduction of phase voltage, ie. *Field Weakening*
- Results are consistent with model prediction





Speed Coil Voltage is Influenced by Stator Current

- Rotor magnet position is estimated based on phase angle of sensor voltage
- Flux from the permanent magnet <u>and</u> phase currents link the sensor loop



$$\tilde{V}_{sense} = \omega_{rm}\left(\lambda'_{mv} + L_{vs}\left(i^r_{ds} + j i^r_{qs}\right)\right) \times 1\angle\theta_{pos}$$

Mutual inductance between stator and sensor loop

Coil Voltage Depends on Back EMF and Stator Currents

- Assuming no current in the sensing coils, sensor coil voltage phasor is expressed as

$$\tilde{V}_{sense} = \omega_{rm}\left(\lambda'_{mv} + L_{vs}\left(i^r_{ds} + j i^r_{qs}\right)\right) \times 1\angle\theta_{pos}$$

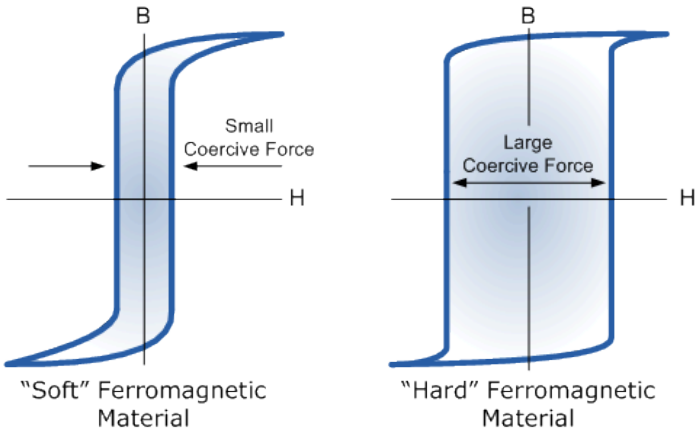
$$\tilde{I}_{as} = I^r_{qs} - j I^r_{ds}$$

- The term $\omega_r \lambda'_{mv}$ coincides with voltage induced by the magnet
- The angle θ_{pos} coincides with the position of the coil relative to the a-phase
- Coil voltage also depends on q-d axis stator currents

There are Two Competing Hypotheses and Solutions

- Hypothesis 1: 'Soft Magnet' theory
  - Barber Nichols engineers acknowledge issue with voltage sensor and has suggested that a 'soft magnet' causes λ'_{mv} to decrease when the generator is under load, citing:
    - Calibration parameters should account for phase current effects
    - Voltage Depression under load

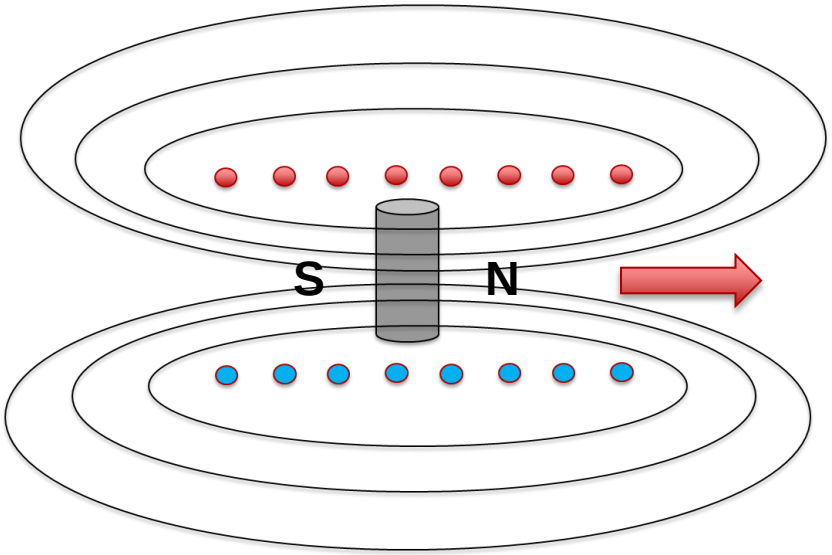
$$\tilde{V}_{sense} = \omega_{rm}\left(\lambda'_{mv} + L_{vs}\left(i^r_{ds} + j i^r_{qs}\right)\right) \times 1\angle\theta_{pos}$$



- Solution 1: 'Remagging' the rotor
  - EEC contracted to re-magnetize the rotor
  - BNI contracted to do a "before and after" evaluation of the rotor

Remagnetizing the Rotor

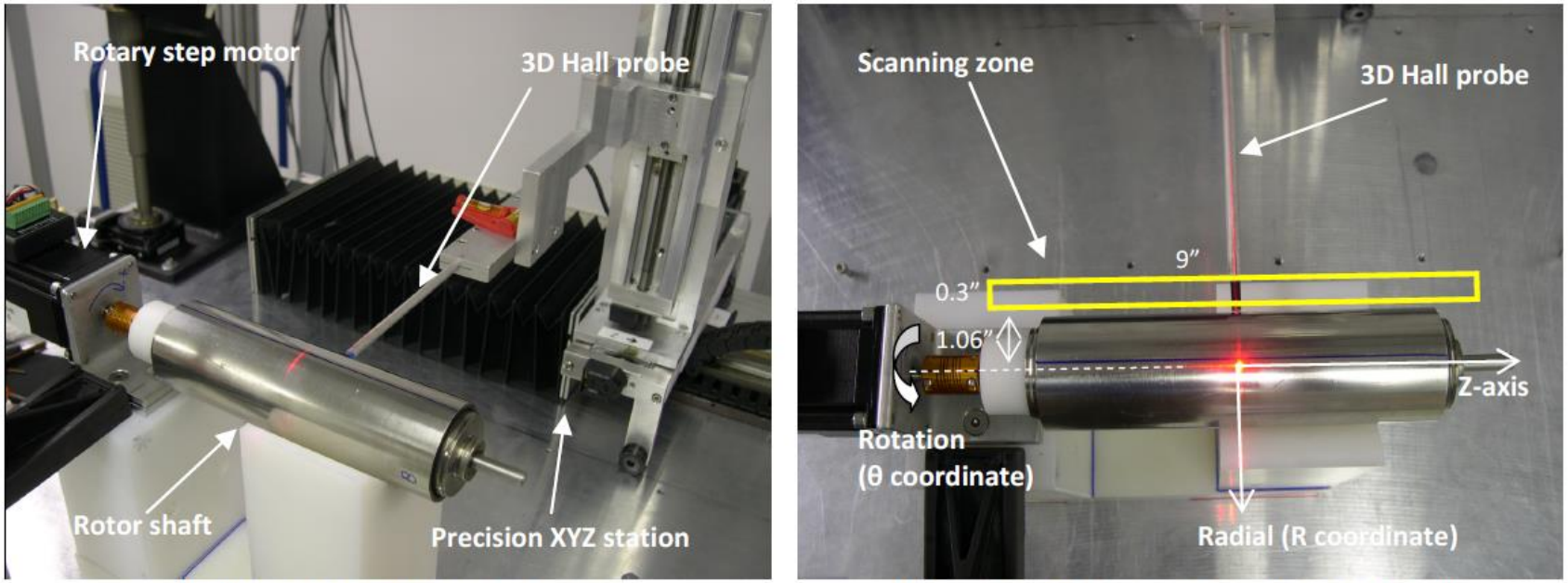
- Remagnetizing occurs in three steps
  - Rotor is heated; this “loosens” the magnetic domains
  - Rotor is placed in a high-strength magnetic field, which realigns the domains



  - Rotor is cooled with domains locked in place

Remagnetizing the Rotor

- Using a Hall Effect sensor and motorized XYZ stage, the magnetic field strength is mapped



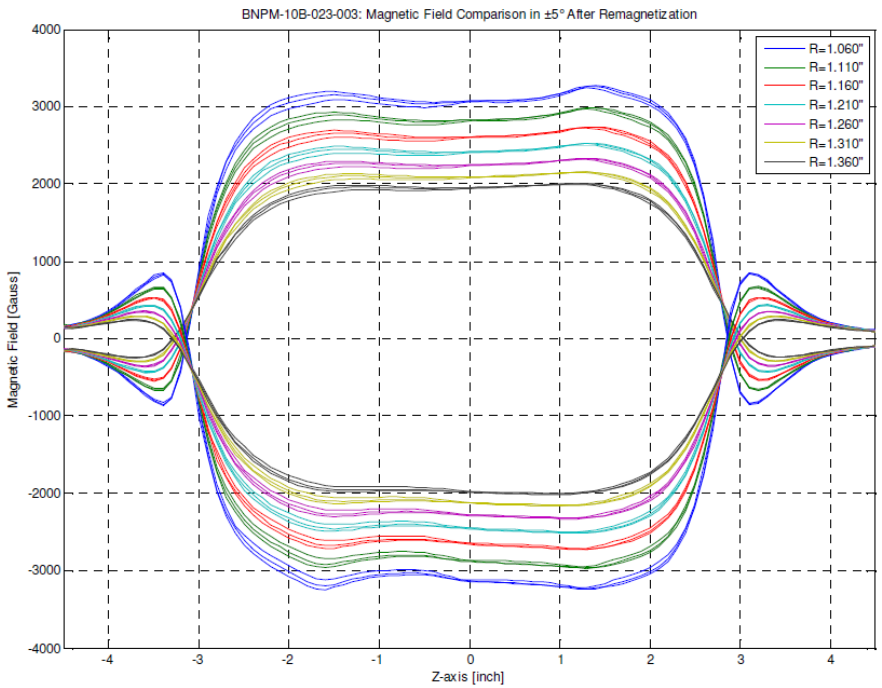
(a) XYZ station with rotary motor (b) Scanning zone and coordinate definition

Figure 3: Test Setup for 3D Field Mapping

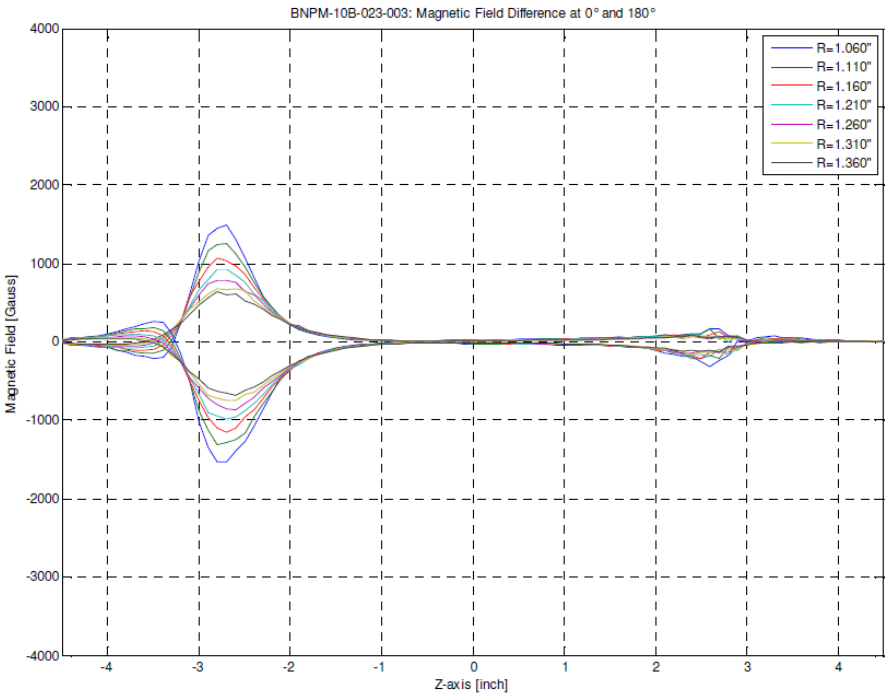
Remagnetizing the Rotor

- Using a Hall Effect sensor and motorized XYZ stage, the magnetic field strength is mapped.

Magnetic field strength



change “before and after”



Remagnetizing the Rotor

- Helmholtz Coil test

001 Rotor

Table 1: Data Comparison Before and After Remagnetization

	Helmholtz Coil Test [mWb·cm]	Peak Field [Gauss]
Before	3.770	2,629
After	3.953	2,719
Change [%]	4.8 ↑	3.4 ↑

002 Rotor

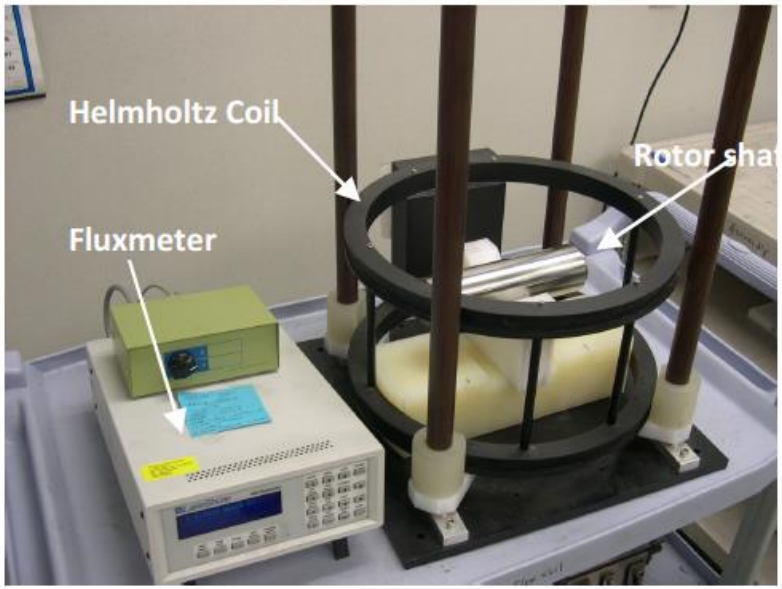
Table 2: Data Comparison Before and After Remagnetization

	Helmholtz Coil Test [mWb·cm]	Average Field at 0° [Gauss]	Average Field at 180° [Gauss]
Before	3.815	1,308	-1,288
After	4.063	1,382	-1,382
Change [%]	6.5 ↑	5.7 ↑	7.2 ↑

003 Rotor

Table 3: Test Comparison Before and After Remagnetization

	Helmholtz Coil Test [mWb·cm]	Average Field at 0° [Gauss]	Average Field at 180° [Gauss]
Before	3.653	1,249	-1,232
After	4.000	1,358	-1,355
Change [%]	9.5 ↑	8.6 ↑	9.9 ↑



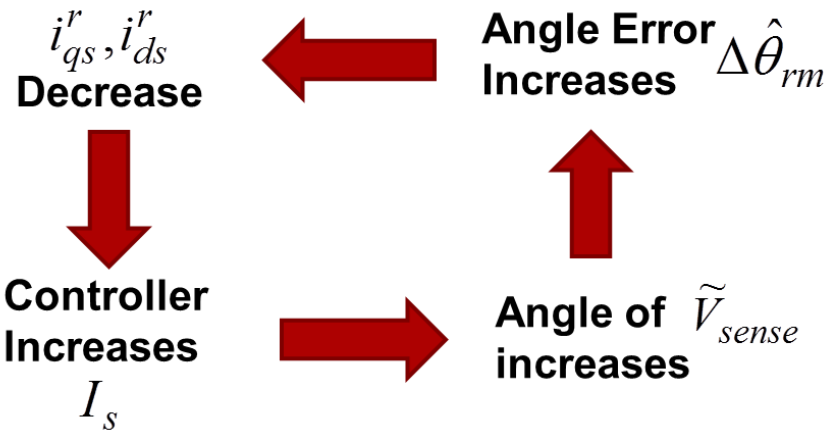
There are Two Competing Hypotheses and Solutions

- Hypothesis 2: Stator Current 'feedback' is driving angle sensor error

$$\tilde{V}_{sense} = \omega_{rm}\left(\lambda'_{mv} + L_{vs}\left(i^r_{ds} + j i^r_{qs}\right)\right) \times 1\angle\theta_{pos}$$

$$\Delta\hat{\theta}_{rm} = \angle\tilde{V}_{sense} + \theta_{pos} + \frac{\pi}{2} - \theta_{rm}$$

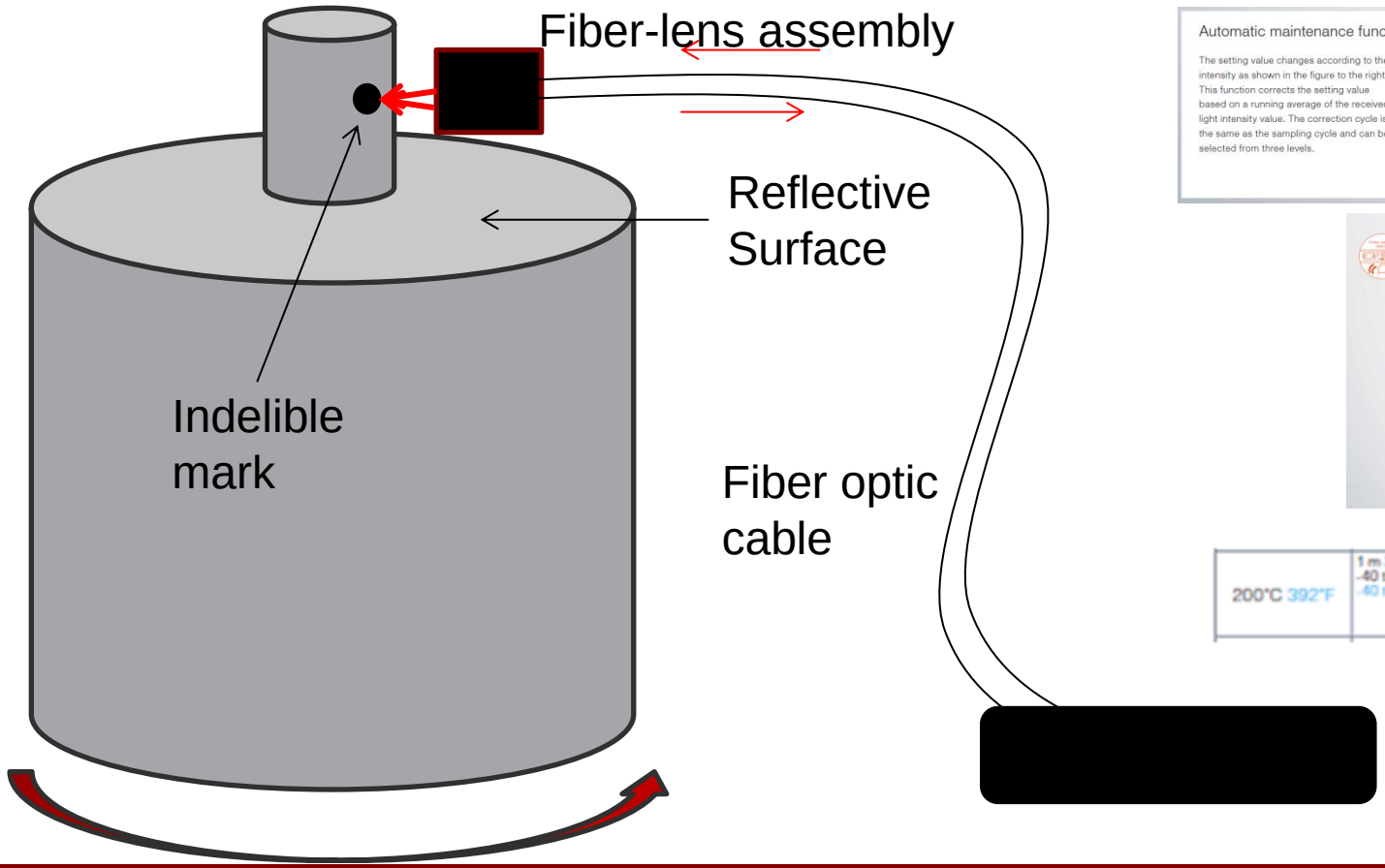
$$i^r_{ds} = -I_s \sin\left(\Delta\hat{\theta}_{rm}\right),\ i^r_{qs} = I_s \cos\left(\Delta\hat{\theta}_{rm}\right)$$

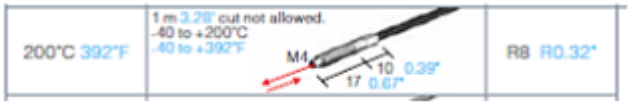


- Solution 2: Develop an Optical Rotor sensor
  - Robust against electrical noise

Optical Rotor Angle Sensing

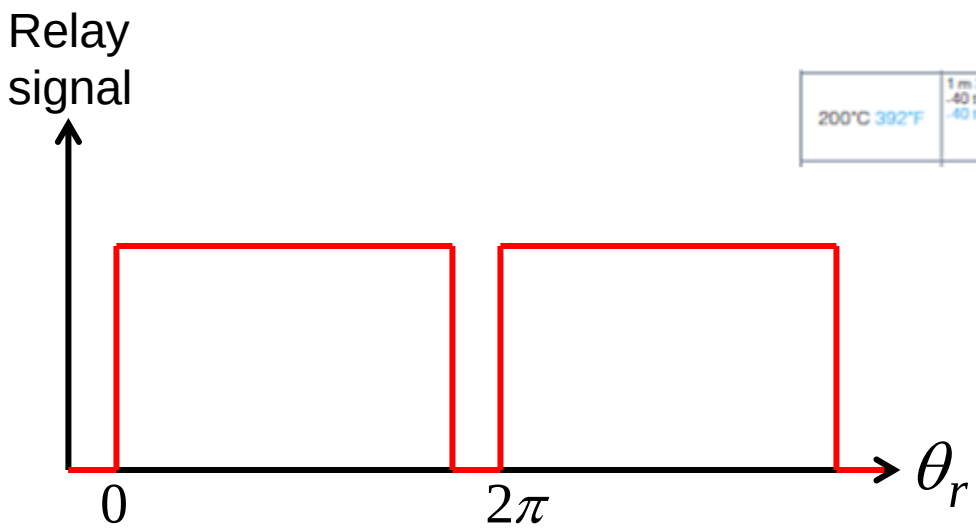
- Fiber Optic Cable carries laser light to a lens assembly

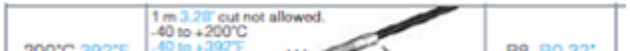




There are design challenges to optical sensing

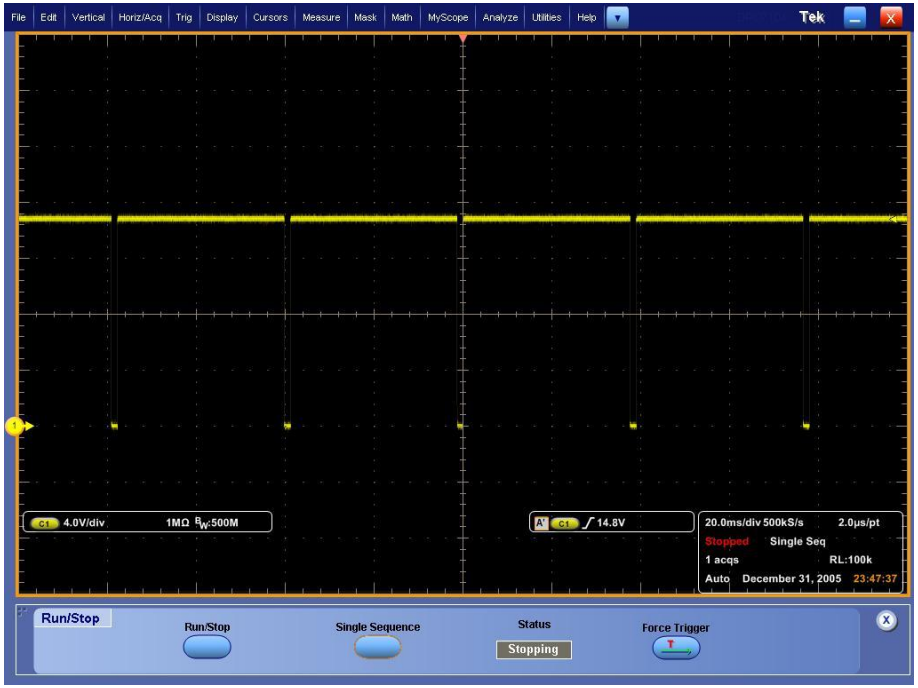
- CO_2 absorbs infrared; Laser light should be visible spectrum
- Commercial Lens assemblies are large; may need to be custom
- High temperatures indicate need for <u>metal-coated fiber</u>
  - Copper Alloy Coating => <u>450 – 600 °C</u>
- A custom circuit is needed to interface with BNI motor drive
- Software changes may be needed to interpret square pulses

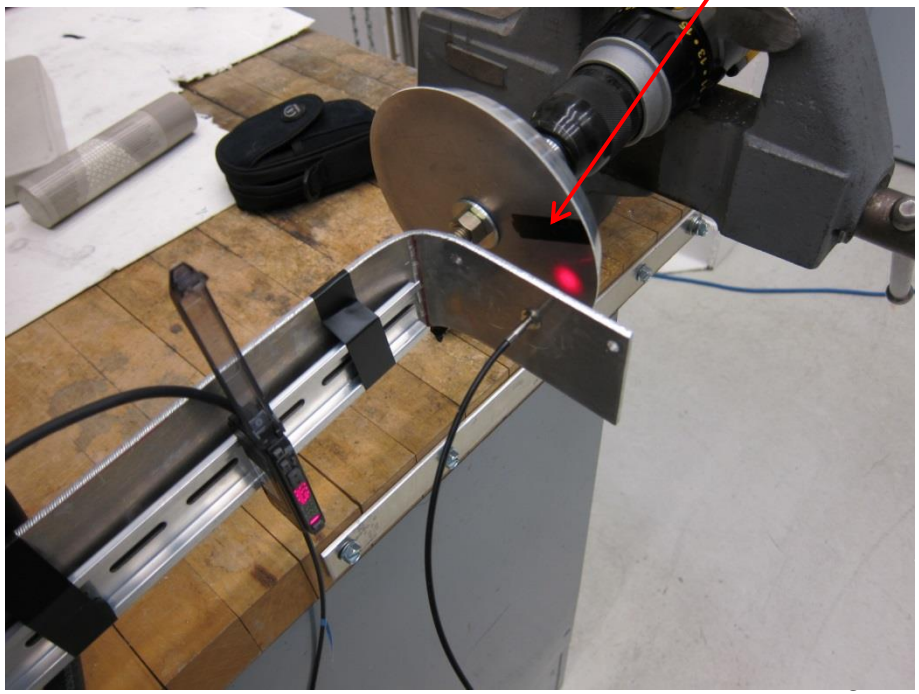




Optical Sensor is Undergoing Bench Top Testing

- A candidate optical sensor is currently being evaluated in a bench top configuration at low speed
  - Geometry / Spot size
  - Signal quality





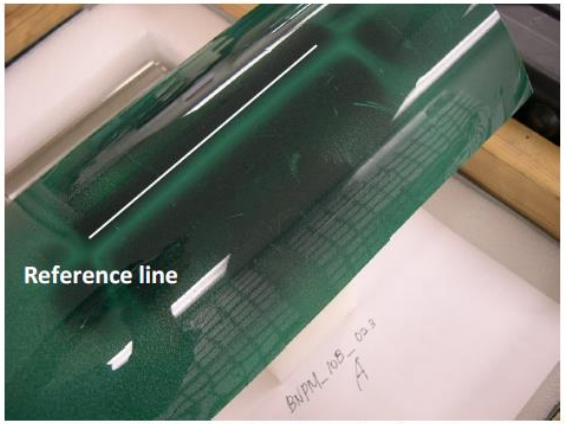
Conclusions

- An electrical machine model has been developed for the generator
- Target power (100 kW) is possible with the current machinery, control hardware and intended control scheme
- Performance issues are consistent with an incorrectly sensed rotor angle
- Two premises and two solutions have been proposed to improve performance
  - Rotor ‘remagging’
  - Optical rotor sensor

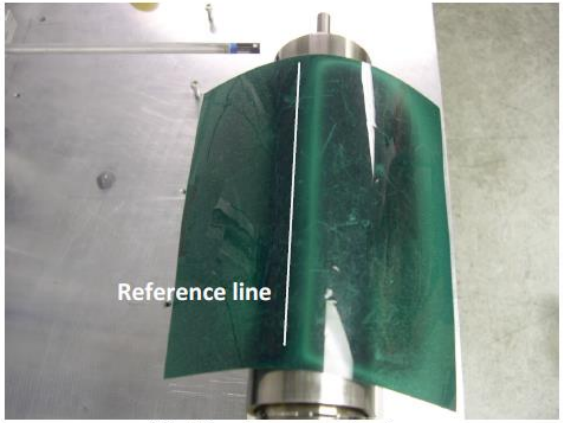
- EXTRAS

Remagnetizing the Rotor

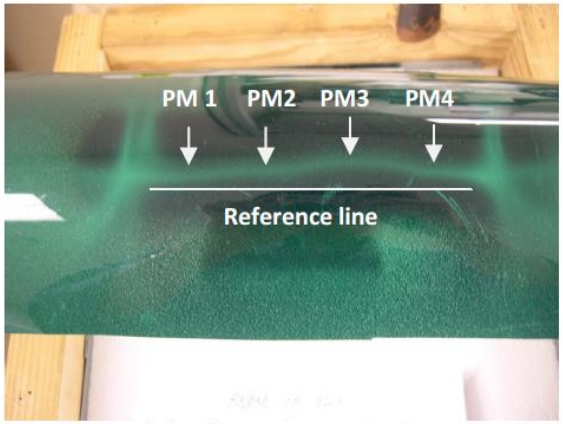
- Magnetic Viewing Film used to check magnet alignment



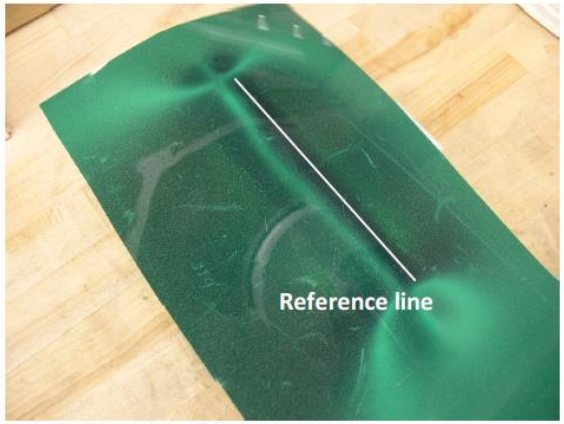
(a) Before Remagnetization



(b) After Remagnetization



(a) Before Remagnetization



(b) After Remagnetization