Permanent Magnet Generators: Design & Testing for Reliability

Jonathan Lynch
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Company Profile

➢ Gearless, PM Generator Wind Turbine Manufacturer

Northwind 100
- 100 kW direct drive turbine for community, net-metering and village power applications
- Manufacturing in 100,000 ft² Barre, VT facility
- Selling to North American and EU markets

Northwind 2.2 MW
- 2.2 MW PM, direct drive turbine
- High energy capture
- Low O&M costs
- Prototypes to install in Q1 2010
PM Generator Manufacturing

- In-house final assembly and testing
- Automated test and data capture
- Integration between manufacturing and operations in turbine database
Generator Requirements

- **Generator reliability is central to our value proposition**
  - Simple gearless drivetrain configuration, dominated by generator
  - Modular design for serviceability
  - Minimal service infrastructure requirements

- **Design focused on long term reliability & availability**

- **Manufacturing focused on minimizing infant mortality**

- **Quantify reliability early through accelerated test program**
  - Qualitative and quantitative testing of generator subsections
  - Use of accelerated testing methods to validate performance
  - Dynamometer testing of complete generator to validate design

- **Demonstrating reliability important to early market acceptance**
Permanent Magnet Generator for Reliability and Efficiency

- 30% lower mass
- 35% lower cost

**Northwind 100A wound rotor DD generator**

**Northwind 100B PMDD generator**

**PM Generator Advantages:**
- Higher efficiency than wound rotor
- Simpler construction, less service
- Eliminates need for field exciter and slip rings
- Reduced cooling requirements

**Northern’s PermaTorq Generator**
(Compared to typical PM designs)
- 20% less magnet materials
- 75% fewer stator coils
- Higher power density
- Easier to manufacture
PM Generator Design Requirements

- 20+ year service life
- High torque density
- Low cogging and ripple torque
- Robust stator winding design
- Simple rotor structure
- On-tower serviceability without external crane
- Controlled environment
- Power converter interface to grid
Reliability Over Product Life

- Different core issues at different stages of life
- Cost effectively maximize time at the floor of the curve

The Bathtub Curve

- Quality issue: Improve with SPC, burn in
- Reliability issue: Move to right!
PM Generator Failure Areas

- **Stator winding failure**
  - Multiple failure mechanisms and modes

- **PM rotor failure**
  - Demagnetization from high temperature/short circuit event
  - Reliability through design, control of operating conditions

- **Bearing failure**
  - Multiple failure mechanisms and modes
Electrical Stator Windings: Cumulative Failure Modes

- **Insulation degradation and breakdown**
  - Phase-Ground
  - Phase-Phase
  - Turn-Turn

- **Open circuit failure**
  - Should be rare with proper design

- **Stator varnish/VPI degradation**
  - Loss of mechanical integrity of coils in slots
  - Increased susceptibility to moisture and environment
  - Increased thermal impedance and temperature rise
  - Increased temperature and movement accelerates failure
Stator Insulation Degradation Processes

- **Thermal aging**
  - Deterioration of insulation properties over natural life

- **Mechanical**
  - Vibration or movement within windings which wears insulation
  - Both normal operation and inrush transient conditions

- **Overvoltage**
  - Damage from lightning, power converter switching

- **Contamination**
  - Chemical deposits that cause insulation deterioration
Designing for Reliability

- **Overvoltage**
  - Design to specific dV/dT conditions with power converter
  - Robust turn-turn insulation system, additional 1st turn insulation
  - Power converter voltage clamp circuit

- **Stator Vacuum-Pressure Impregnation (VPI)**
  - High stator mechanical integrity, drives out voids
  - Increased thermal conductivity, reduced hot spots

- **Power converter interface to grid**
  - No over-current operation, no inrush current operating conditions
  - Balanced phase currents

- **Environmental**
  - Closed cooling system; isolate from contaminants
Stator Coils

- Random wound coils
  - Harder to control manufacturing quality
  - Data indicates higher field failure rates
  - Less control over turn-turn and phase-phase voltages

- Formed coils – distributed winding

- Formed coils – concentrated winding
Insulation Life Estimates During Design

- **Insulation Life**
  - An insulation material should have an average life of about 20,000 hours (2.3 years) if operated continuously at its temperature rating
  - For 20 year life, the chart indicates the max continuous operating temperature would about 155°C

- **Alternate method**
  - General rule of thumb: For every 10°C below the insulation rating a machine is operated at, insulation life is doubled (Arrhenius rate law)
  - Continuous operation of a Class 200 insulation system would result in the following life expectancy
    - Operation @ 200°C – 2.3 year life
    - Operation @ 190°C – 4.6 year life
    - Operation @ 180°C – 9.1 year life
    - Operation @ 170°C – 18.3 year life

- **Verify through testing!**
Reliability Test Program Goals

- Quantify expected generator reliability through careful accelerated tests
- Increase understanding of failure mechanisms and failure modes to guide ongoing improvement process
- Establish initial reliability database to be augmented with field data over time.
- Share data with customers to aid market acceptance
Reliability Testing Methods

- **Test to Failure**
  - Test to Failure
  - Normal Stress w/ Weibull Plotting
  - Accelerated Testing
    - HALT
    - Calibrated
  - Normal Sample Size
    - Normal Test Duration
  - Reduced Sample Size
    - w/ Extended Test Time

- **Success-Run**

- **Reliability Characterization**
Part Failure Rate as Weibull Function

- Failure distribution moves from exponential to compact normal shape with increase in Weibull slope value
- Weibull factors determined through testing, empirical history
- Use as basis for understanding life requirements…
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Probability Density Function

Weibull Cumulative Density Function

Unreliability, $F(t)$
Determining Weibull Factors with Small Sample Size

Sample Size = 6:

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<tr>
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<td>5</td>
<td>73.6%</td>
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<tr>
<td>6</td>
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Typical Weibull slope values:
- Electrical: $\beta = 1.5$ to $2$
- Complex Mechanical: $\beta = 1.5$ to $2$
- Basic Fatigue: $\beta = 2$ to $2.5$

Accelerated Testing Needed!
Success-Run Testing: Sample Size?

- Demonstrate reliability $R$ to confidence level $C$ by testing $N$ part samples for desired design life without failure:

- Use Bayes’ formula:
  \[ R = \left(1 - C\right)^{1/N} \]

- Rearranged to:
  \[ N = \frac{\ln(1 - C)}{\ln(R)} \]

- **Examples:**
  - $R = .95$, $C = .50$, Life = 20 yr: $N = 14$ test samples
  - $R = .99$, $C = .50$, Life = 20 yr: $N = 69$ test samples
Success-Run Testing: Sample Size?

- Can reduce the number of samples by testing for longer than one Design Life
- Equate Bayes’ Theorem with Weibull distribution: obtain the Lipson Equality:

\[ X_{\text{new}} = X_{\text{old}} \times \beta \sqrt{N_{\text{old}} / N_{\text{new}}} \]

Where \( N \) = number of samples, \( X \) = life requirement, \( \beta \) = Weibull slope parameter (shape) for part

- For \( R = 0.95, C = 0.50, X = 100 \) hrs. >>> 14 samples required by Bayes’
- If want to reduce to 7 samples: >>> \( X_{\text{new}} = 130 \) hrs. for \( \beta = 2.5 \)

Accelerated Testing Needed!
Acceleration Factor

Acceleration Factor: Ratio of life under normal stress conditions to life under accelerated stress conditions

\[ AF = \left( \frac{\text{Stress}^{\text{Accel}}}{\text{Stress}^{\text{Norm}}} \right)^m \]
Life – Stress Models

➢ **Inverse Power Model** – applies to mechanical stress, thermal & mechanical fatigue

\[
AF = \left[ \frac{\text{Stress}_{\text{Accel}}}{\text{Stress}_{\text{Norm}}} \right]^m
\]

\[
L_{\text{Accel}} = \frac{L_{\text{Norm}}}{\left[ \frac{\text{Stress}_{\text{Accel}}}{\text{Stress}_{\text{Norm}}} \right]^m}
\]

or:

\[
AF = e^{\left[ \frac{E_a}{K_b} \right] \left[ \frac{1}{\text{Stress}_{\text{norm}}} - \frac{1}{\text{Stress}_{\text{accel}}} \right]}
\]

Where:

- \(m\) = S-N curve slope
- \(E_a\) = Activation Energy (varies by failure mechanism)
- \(K_b\) = Boltzmann’s constant = 8.61739 X 10^-5 eV/°K

➢ **Arrhenius Model** – applies to chemical reactions and diffusion mechanisms. Widely used for insulation life, electrochemistry, etc.
Accelerated Test Example

- Electronic device undergoing thermal cycling and fatigue in design operation
- If 3 cycles per day with 25°C thermal cycle >> 21,900 cycles in 20 years

- If test with 125°C thermal cycles, then life for thermal cycling is?
  (Typical \( m \) for electronics is 2.5)

- **392 thermal cycles for accelerated test**
Possible Sample Test Sequences

**Samples 1-6**
- High Temp. & High Humidity
- High Temp. & Low Humidity
- Vibration
- Temperature Cycling
- Inspection

**Samples 6-12**
- Thermal Shock
- Power & Temp. Cycling
- Humidity
- Low level Vibration w/Temp. Cycling
- Inspection
Summary

- Use reliability as a core design criteria, can’t add it later
- Establish consistent reliability methods and language throughout the organization
- Ensure reliability at beginning of service life through manufacturing and installation quality
- Partner with customers to maximize long term reliability
- Continuous learning through product lifecycle
Jonathan Lynch
jlynch@northernpower.com
802-461-2824

Northwind 2.2 MW

Northwind 100