IMPROVING TURBINE RELIABILITY THROUGH COMPONENT DESIGN OPTIMIZATION

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Key learnings

1. Reducing Wind LCoE is important for the industry

2. Improving turbine reliability can help reduce LCoE

3. Pitch systems currently used by the industry is a major failure component

4. Significant opportunity exists to improve electric pitch system reliability through design optimization

5. DNV GL LCoE model shows that Moog Pitch System 3 could save up to $782K/year for a typical 150MW wind farm

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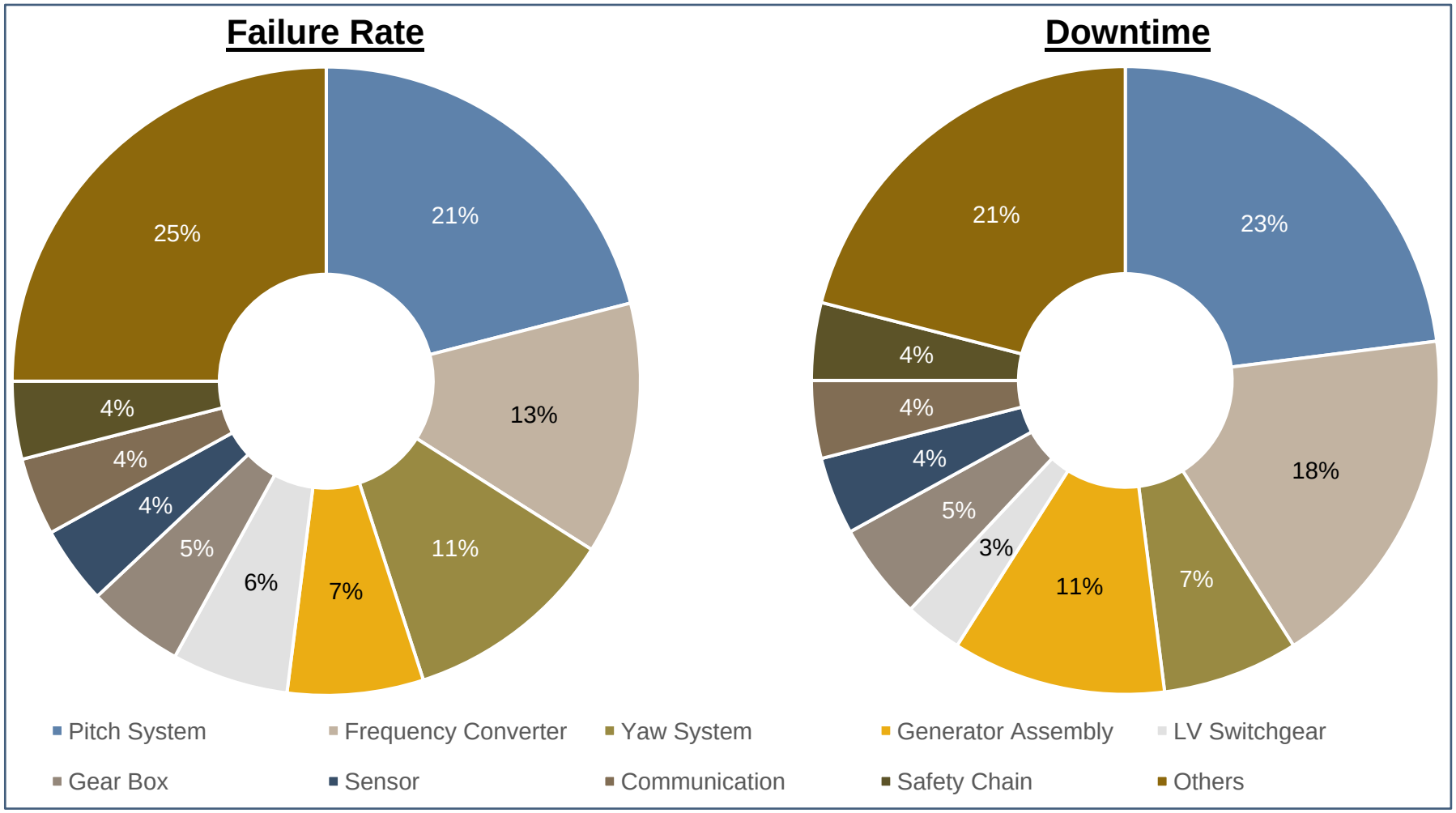
The Reliawind research identifies pitch system as the #1 component contributing to turbine failure & downtime



Source: Reliability and maintenance of wind turbines challenges and perspectives, Dr.-Ing. Katharina Fischer, Fraunhofer Institute for Wind Energy and Energy System Technology

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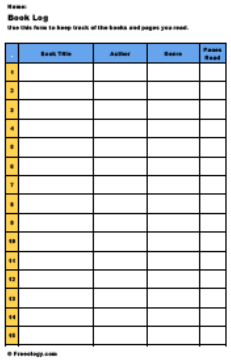
Pitch system facts

- < 3% of wind farm CAPEX investment
  (source: Moog, Bloomberg)
- 20 to 30% of wind turbine O&M expenses
  (source: Top 10 Wind Turbine OEM interviews by Moog)
- 21% of wind turbine failure rate
  (source: Reliawind)
- 23% of wind turbine downtime
  (source: Reliawind)

This year, Moog partnered with DNV GL for a project with the following objectives:

- More accurately quantify the impact of pitch system reliability on turbine failure rate and downtime
- Quantify the reduction in LCoE due to improvements in pitch system reliability

Failure rate benchmarking based on operational data



Fault logs

Failure tracking logs

Benchmarking Dataset

Operator reports

69 Projects
5.3GW installed capacity
4 Million Turbine Days
Europe, USA and China
Rating between 1.5MW and 3MW

Pitch system failure analysis results

	Failure rate[1]	Projects	Turbines
North America	0.6	23	907
China	0.7	3	30
Europe	0.9	19	393
All regions – 1.5 MW < X < 2.5MW	0.5	38	1,136
All regions – 2.5 MW ≤ X < 3.0MW	1.6	7	194
Overall	0.7	45	1,330

[1] Incidents per turbine per year from projects with mean downtime > 3 hours

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Pitch system reliability benchmarking study reconfirms that:

- Pitch systems (electric and hydraulic) are a major failure component in a wind turbine

- The larger the turbine, the greater the failure rate of pitch systems

Design improvement analysis (2/2)

Current Industry Design

Axis Box including Servo Drive

Battery Backup

Component Count	3,843
Cable Connection Count	607
System Reliability Hours	5,769

Moog Pitch System 3

Axis Box including Pitch Servo Drive and Pitch Capacitor Module

Component Count	1322
Cable Connection Count	318
System Reliability Hours	18,743

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High performance motors can reduce wear and stress on pitch bearings

AC Servo Motor

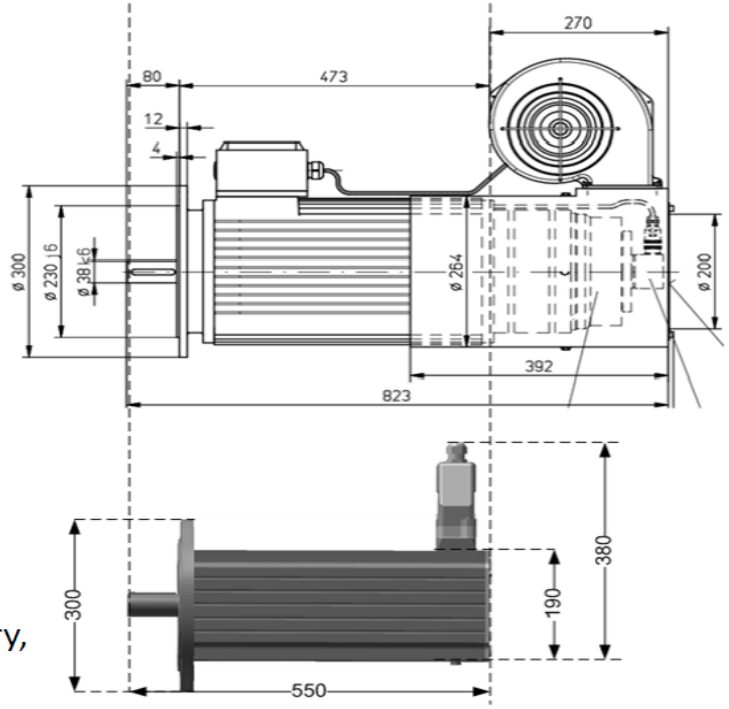
Typical sample for a 3MW WTG: PMC vs. DC Motor

DC

- Motor weight = 148 kg
- Rotor inertia = 0,08 kgm²
- Active cooling fan necessary

AC Servo

- Motor weight = 54 kg
- Rotor inertia = 0,02 kgm²
  - ➡ *improved dynamic behavior*
- No active cooling necessary, convection cooled
  - ➡ *higher reliability, easier maintenance*



Drawings to scale!

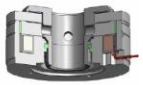
DC Motor
FGVH-132XL

PMC Motor
PMC6-L60

PMC Brake Technology

Feature Set:

- ✓ Holding brake (as drive stops feathering run)
  - centered by permanent magnets
  - no Wear
    - *maintenance free*
  - ➡
- ✓ Standardized permanent magnet brake
  - *high quality & reliability*



Design:

- ✓ Front end bell integration for optimized heat dissipation
- ✓ Maximum peak torque capability per size
- ✓ Minimum installation space

Moog pitch system design optimization study confirms that:

- **EM offers significant potential for reliability improvement due to:**
  - Pluggable (highly integrated) electronics design for drives
  - AC servo motor technology
  - Advances in ultra capacitors design

Potential cost of energy reductions through improved pitch system design for a typical 3MW turbine

Description	LCoE [$/MWh]	LCoE Savings [$/MWh]
Current industry design	53.31	-
Moog Pitch System 3	51.61	1.70

Total savings/year for typical wind farm, 150MW @35% capacity factor will be:

1.70 ($/MWh) x 3.0 (MW) x 50 (turbines) x 365 (days) x 24 (hours) x 0.35 (capacity factor) = $782K/year

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Conclusions

- Average pitch systems failure rate for onshore turbines between 1.5MW and 3.0MW is 0.7 failures per turbine per year
- Turbines >2.5MW experience higher pitch system failure rates than turbines <2.5MW
- Tests validated by Moog shows that it is possible to improve pitch system reliability (for a typical 3MW turbine) to 0.16 failures per turbine per year through design optimization
- DNV GL LCoE model shows that Moog pitch system 3 could **save up to $782K/year** for a typical 150MW wind farm

THANK YOU

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