Predictive Maintenance of Permanent Magnet (PM) Wind Generators

by

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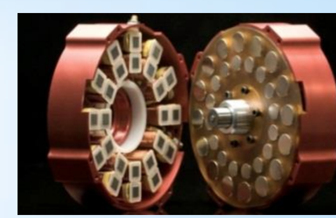
Presentation Outline

1. Introduction
2. Maintenance of PM Wind Generators
3. Fault Diagnostic Techniques for Electrical Machines
4. PM Machine Faults Types and Analysis
5. Detection of Static Eccentricity (SE)
6. Conclusion







1. Introduction

❖ Why Wind Energy?

- It is renewable and abundant
- It is a fast growing renewable energy source
- It has now established itself as a mainstream renewable electricity generation source, and plays a central role in an increasing number of countries' immediate and longer term energy plans

- From 1997 – 2012, wind power had an average growth rate of 28%
- As at 2012 year-end:
  - There was **282GW** global installed wind power capacity
  - It accounted for 27% of total global renewable energy supply

Source: Global Wind Energy Council (GWEC)

- *GWEC* envisages that wind power would meet between **7.7% - 8.3%** of global electrical demand in 2020 and **14.1% - 15.8%** in 2030.

❖ PM Generators in Wind Turbines

- There is an increase in manufacturing shift towards PM generators and direct-drive system

Global cumulative installed capacity

	2004		2011
World market: 100%			
Top 10 manufacturers:	>95%	➡	78.8
Geared generator system:	>78%		<75%
Direct-drive (DD) generator system:	<20%		>25%
DD excitation system:	PM<5% EE>15%		PM>EE (actual figure not available)

- Field excitation provided by PMs:
  - excitation loss is reduced
  - power electronics converters could be integrated since their price has been declining over the years

- Suitable for direct-drive wind turbine system which is based on a simple principle, ***fewer rotating components*** compared with geared-drive system:
  - reduced mechanical stress
  - increased technical service life

  → *improved maintainability and efficiency*

  - increased power production of the turbines
  - could be deployed in regions with low wind speed → *Optimization of wind resources and better yield*

2. Maintenance of PM Wind Generators

❖ Challenges of Deploying and Maintaining PM Generators in Wind Turbines

1. Reliability issues resulting from the operation of PM generators in both normal and hash environmental conditions, *e.g. demagnetization*.
2. Difficulty in accessing wind farms in remote locations for repairs, *e.g. offshore*.
3. Long downtime associated with generator component in wind turbines, table 1.

Table 1. Components and failure indices

Components	Annual Failure Rate	Down Time Per Failure (Days)
Electrical System	0.57	< 2
Electronic Control	0.43	< 2
Sensors	0.25	< 2
Hydraulic System	0.23	< 2
Yaw System	0.18	2 – 3
Rotor Hub	0.17	> 4
Mechanical Brake	0.13	2 - 3
Generator	**0.11**	**> 7**
Rotor Blades	0.11	> 3
Gear Box	0.1	6 - 7
Support & Housing	0.1	> 3
Drive Train	0.05	> 5

- Challenges 1-3 can be overcome by implementing **predictive maintenance strategies.** It is based on **online condition monitoring** using electrical machine fault diagnostic techniques.

- Predictive maintenance combines the best features of both preventive and corrective maintenance.

3. Fault Diagnostic Techniques for Electrical Machines

❖ Major Challenge in Applying them in PM Wind Generators

- Intermittent nature of wind resources causes recurring transient state in wind generators, thus, this need to be overcome in the development of fault diagnostic schemes for predictive maintenance purposes.

Furthermore, unlike induction machines, there are no standard online diagnostic techniques for PM machines and for the wind industry.

❖ Types of Fault Diagnostic Techniques

The diagnostic technique widely used is:

- ***Signal-based***
- mechanical vibration analysis
- acoustic analysis
- shock pulse monitoring
- temperature monitoring
- motor current signature analysis
- electromagnetic field monitoring using search coils
- oil and gas analysis, infrared analysis
- partial discharge measurement
- RF injection

Others are:

- ***Artificial Intelligence-based***
- Neural network
- Fuzzy logic
- Genetic algorithm

- ***Machine-theory-based***
- Winding function approach
- Magnetic equivalent circuit

- ***Simulation-based***
- Finite element analysis

- **Only signal-based techniques using various standard signal processing methods are employed at industry level for the following reasons:**

1. Machine signals can be measured and thus severity of faults can be quantified.
2. Accommodate in-situ and non-invasive analysis.
3. Expert knowledge is not required in making decision.

❖ Standard Signal Processing Methods

- **Non-Parametric (Fourier-based): Periodogram and Short-time Fourier Transform**

Table 2. Periodogram (*for steady-state condition*)

Method	Advantages	Disadvantages
Periodogram (It uses FFT; a non-parametric method)	a. Ease of implementation.	a. Long measurement time is needed (=>30s) and as such stationary signal is not guaranteed. b. Large number of samples (=>100k) need to be collected, thus increasing memory and cost requirements of data acquisition devices.

- To overcome the problem of long measurement duration and large number of samples, the parametric method alternative is proposed. Examples are Estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT), Multiple Signal Classification (MUSIC) etc.

\- Both ESPRIT and MUSIC algorithms use same technique but ESPRIT is superior to MUSIC in accuracy and as such it is preferred.

- **Estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT)**

- The basic principle is that if a signal depends on a finite set of parameters, then all of its statistical properties including its power spectrum can be expressed in terms of these parameters. This is done using parametric models that relate to the eigenvector decomposition of the correlation matrix to estimate the discrete part of the spectrum.

Table 3. ESPRIT (*for steady-state condition*)

Method	Advantages	Disadvantages
ESPRIT (a parametric method)	a. Very high accuracy. b. Very short measurement time (=<3s) and as such stationary signal is better guaranteed. c. Small number of samples is required (=<10 k).	a. Computational time is longer than FFT. *(ESPRIT-60s;10ks)* *(FFT-1s;600ks)* b. Algorithm is more complex; computes Eigen-value and covariance matrix.

Table 4. Short-Time Fourier Transform (*for transient condition*)

Method	Advantages	Disadvantages
Short-Time Fourier Transform (STFT)	a. It is based on the conventional Fourier Transform: Simple and robust	a. The averages of time and frequency are never correctly given, hence, trade-off between the time and frequency localization of the spectrogram. b. It scrambles the energy distribution of the signal with that of the window function.

Others are: Hilbert Transform, Wavelet Transform, Cohen-Class Distribution (Wigner-Ville, Choi-Williams…) etc.

- ***Improved* Cohen-Class Distribution (for transient condition)**
  To overcome the disadvantages above, a type of Cohen-Class Distribution namely, Zhao-Atlas Marks (ZAM) Distribution is proposed.

- It is a quadratic-time frequency technique that computes the energy level of a signal and its distribution across time-frequency domain.

Table 5. Zhao-Atlas Marks (ZAM) Distribution (*for transient condition*)

Method	Advantages	Disadvantages
Zhao-Atlas Marks (ZAM) Distribution	a. Independent of the choice of window and as such, no cross-term artifact in time-frequency domain. b. Better resolution than STFT	a. It is a spectrogram and as such, the exact magnitudes of energy spectrum is difficult to obtain.

4. PM Machine Faults Types and Analysis

❖ Common Faults Associated with PM Wind Generators

Table 6. PM generated fault types

FAULTS	ELECTRICAL	MECHANICAL				
Types	Winding faults	Core or lamination	Magnet damage: *Broken/displaced PMs*	Eccentricity	Broken/misaligned shaft	Bearing Faults
Sub-types	Short circuit ϕ-ϕ,3-ϕ,ϕ-grd inter - turn  Open circuit High impedance	-	- 	Static Dynamic	-	- 
Parts of generator affected	Stator	Stator Rotor	Rotor	Rotor	Shaft Rotor	Shaft Rotor
Frequency of occurrence	Frequent	Very Rare	-	Frequent (Axial flux) Rare (Radial flux)	Rare	Frequent
Severity (danger and damage)	High	Cata-strophic	Medium	Low	Medium	Medium

5. Detection of Static Eccentricity (SE)

❖ 2D Analysis: Axial-flux PM Machine

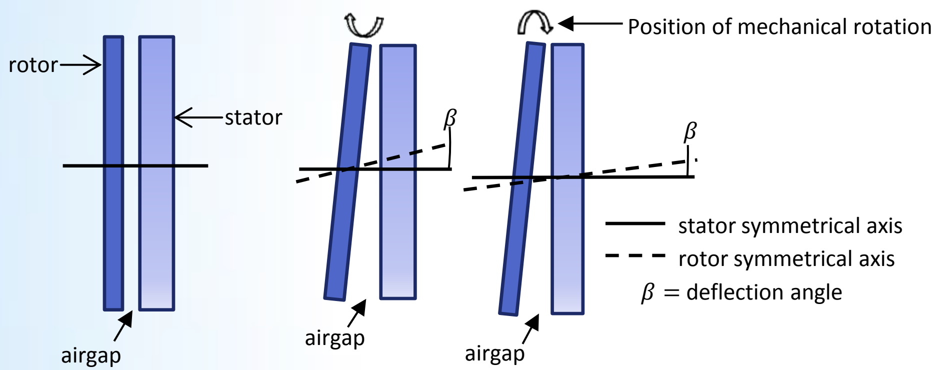


Fig.1. Healthy (left) Static Eccentric (right)

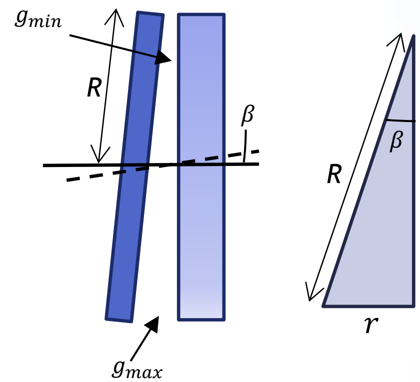


Fig.2. Cross-section of asymmetric air gap (triangle)

g = original air-gap length

$r = g_{max} - g = g - g_{min}$

$SEF = \frac{r}{g} \times 100\%$ (*SEF: Static Eccentricity Factor*)

$$\beta = \sin^{-1}\left(\frac{r}{R}\right)$$

$$SEF = \frac{R.\sin(\beta)}{g} \times 100\%$$

SEF increases as outer radius/diameter increases, thus, AFPM machine is more susceptible to SE than RFPM machine because of its larger aspect ratio.

$$\boxed{\boldsymbol{g_1 = g\left(1 \pm \frac{r}{g}\right)}}$$

g_1 is the effective air-gap length

In the absence of eccentricity,

$g_1 = g$

❖ Vibration Monitoring

- SE is a mechanical fault, therefore vibration (mechanical signal) is chosen to be analysed. Current and voltage monitoring are also fitting since SE results in asymmetric airgap flux distribution.

- SE Vibration Fault Frequencies

- Vibration harmonics (*increased magnitude*) arise at frequencies relating to the following:

'Twice-the-line' frequency, i.e., $2f$, where f is the fundamental frequency of the line current.

- The 2nd harmonic of the magnetic force. This is present in the vibration spectrum.

▪ Steady State Detection Using ESPRIT

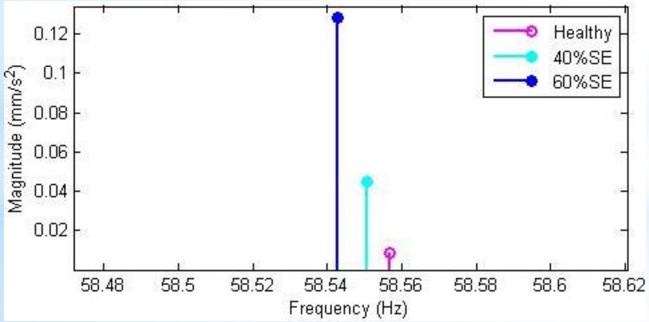


Fig.3. Fault harmonics at $2f$

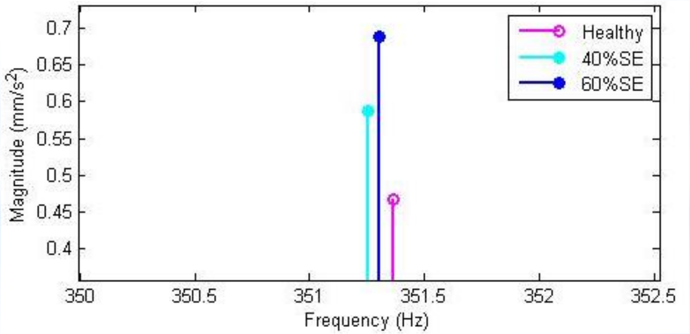


Fig.4. Fault at 350Hz; frequency of the 2nd harmonic of the magnetic force

- ## Transient Detection Using ZAM

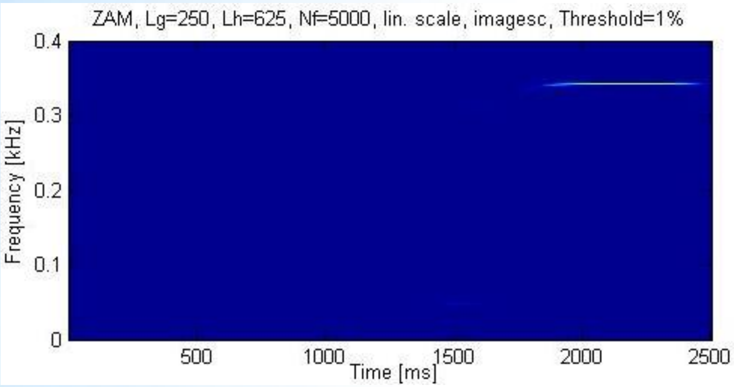


Fig.5. Healthy spectrogram

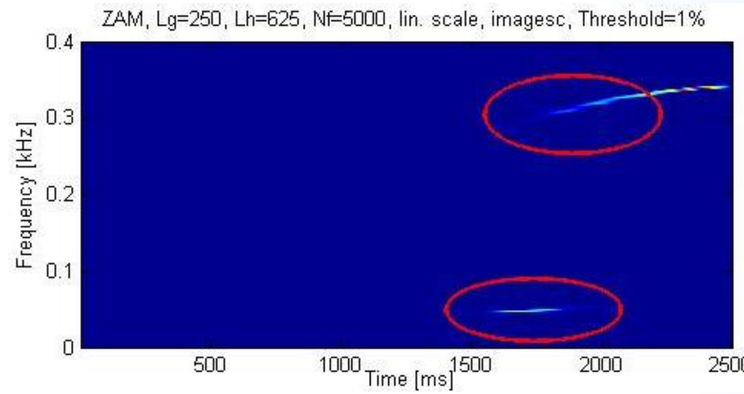


Fig.6. Spectrogram for 40% SE

The ellipses indicate visible harmonics at 58Hz and 350Hz; i.e., $2f$ and 2nd harmonic frequency of the magnetic force respectively

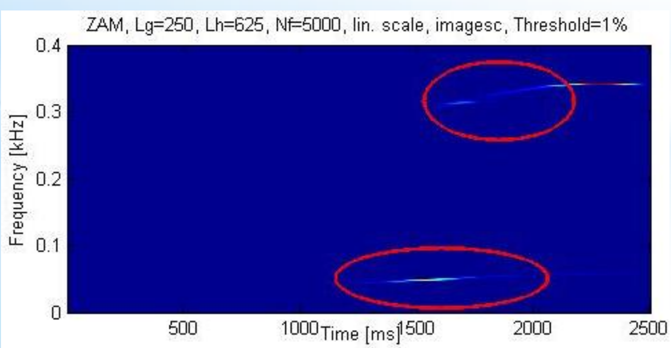


Fig.7. Spectrogram for 60% SE

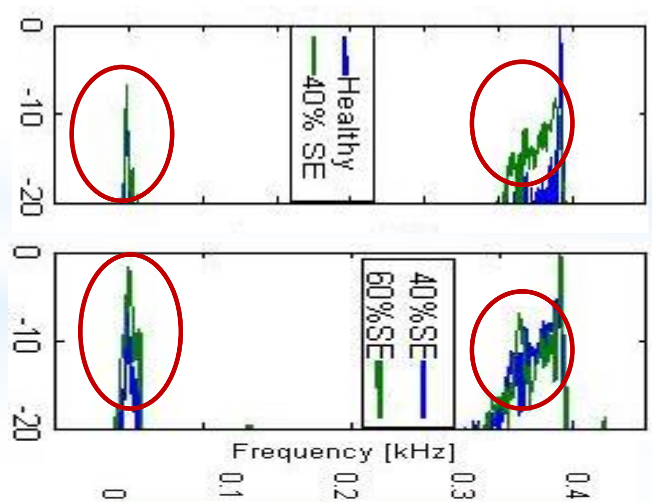


Fig.8. Energy spectrum of the vibratory response

Increase in spectrum energy level across time-frequency domain is obtained in conditions of SE.

6. Conclusions

- The techniques explored are effective for vibration monitoring for both steady-state and transient conditions.
- The problem of fault detection due to non-stationary phenomenon associated with wind generators can be overcome using ESPRIT as spectral estimator.
- ZAM distribution offers high energy resolution and as such is effective in computing the energy distribution of vibration signal across time-frequency domain.
- Predictive maintenance can reliably be built on condition monitoring strategies based on the techniques.

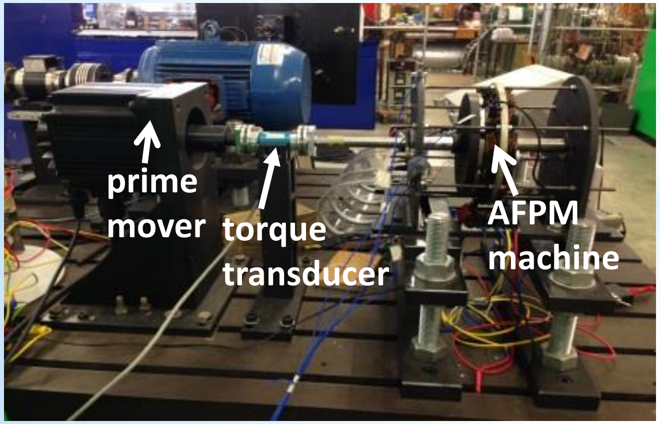


Fig.9. Test rig (left) and data acquisition devices for the signal capture (right)

Thanks for listening!