Reliability Analysis And Condition Monitoring of a Horizontal Axis Wind Turbine

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M.Engineering Thesis Presentation

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Contents of Presentation

- Condition Monitoring – Overview of previous work
- Problem Statement
- System Description
- Reliability modeling and Analysis
- Reliability Analysis results and identification of problems
- Condition Monitoring System Design
- CM System Implementation
- Conclusion and Recommendations

Previous Work in CM for Wind Turbines

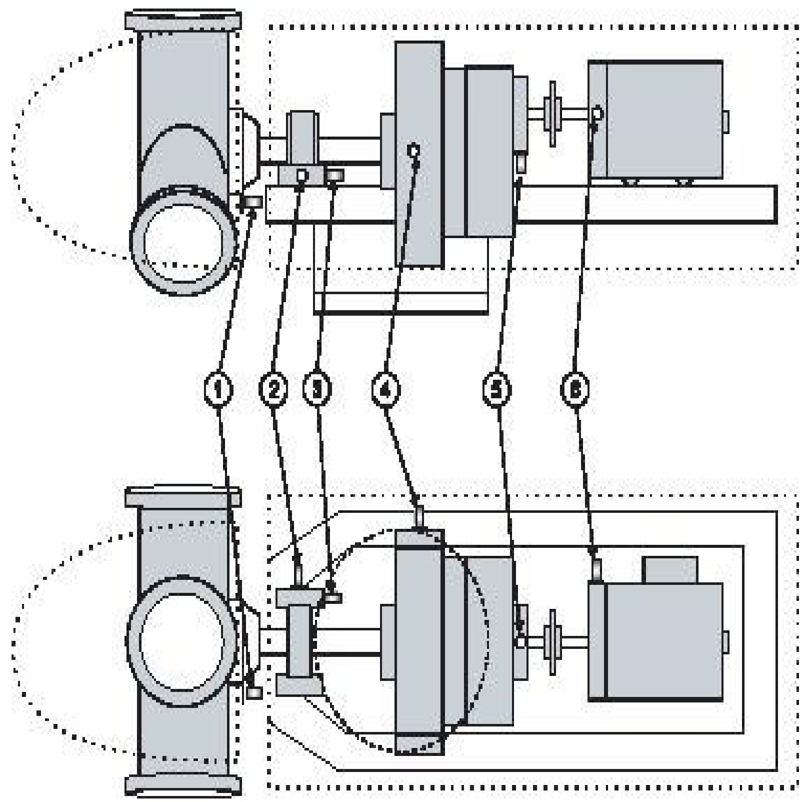
- Many Researcher have done work in several directions

- P Caselitz and Giebhardt have worked for several years in Germany on CMS for WTs

    - Institute for Solar Energy Tech ISET Germany

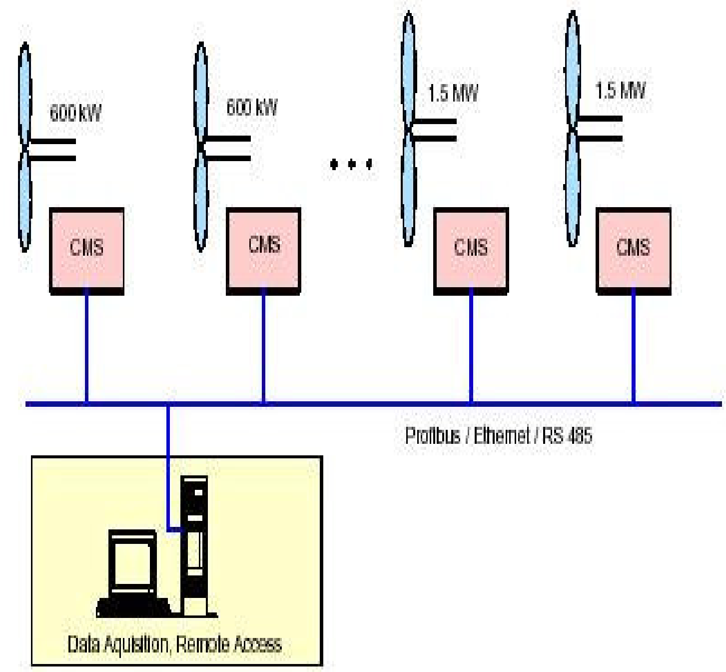
    - Discussed the CM development of a 600 kW WT

    - Remote Access is used by interconnecting the data acquisition module and PC



Previous Work in CM for Wind Turbines

- Separate PC for Data acquisition
- Pricing Issue for Smaller WTs
- A solution is required… !

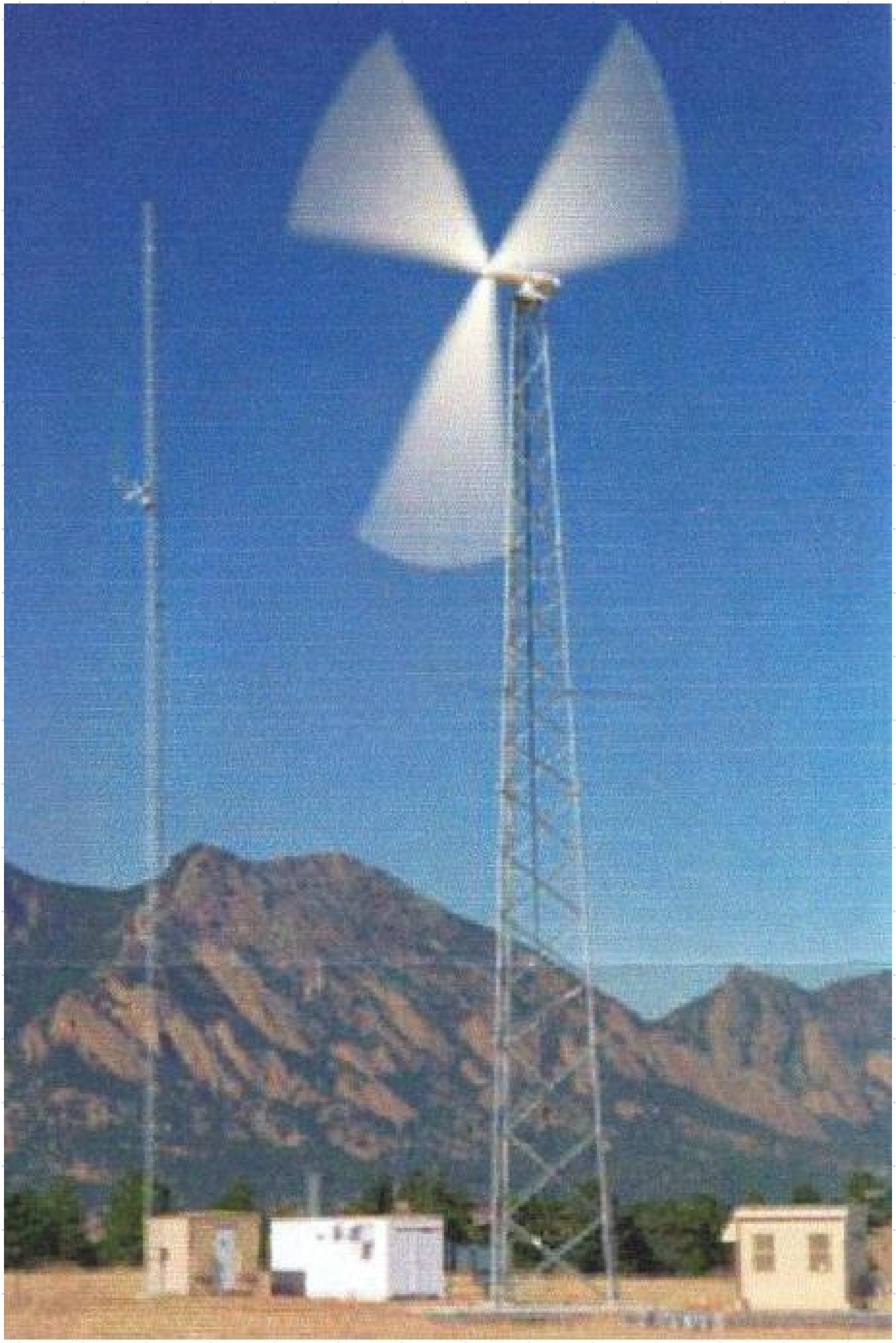


Purpose of Research – Problem Statement

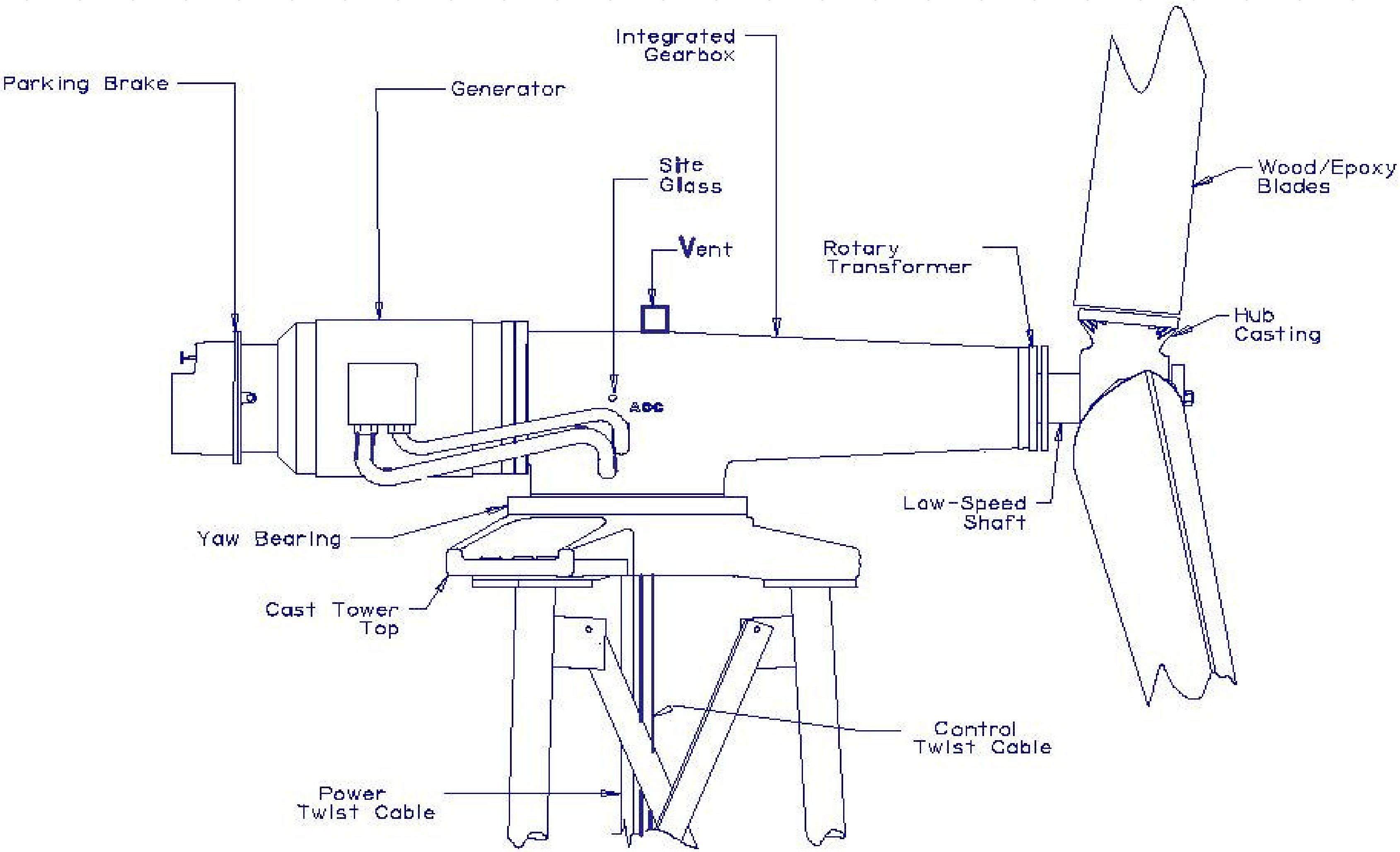
- An efficient and cost effective solution for CM
- CM can not be Generic initially
- CM cannot monitor every thing without a reason… !
- To Identify the components that will require CM a in-depth Reliability Analysis is required

AOC 15/50 – Wind Turbine System

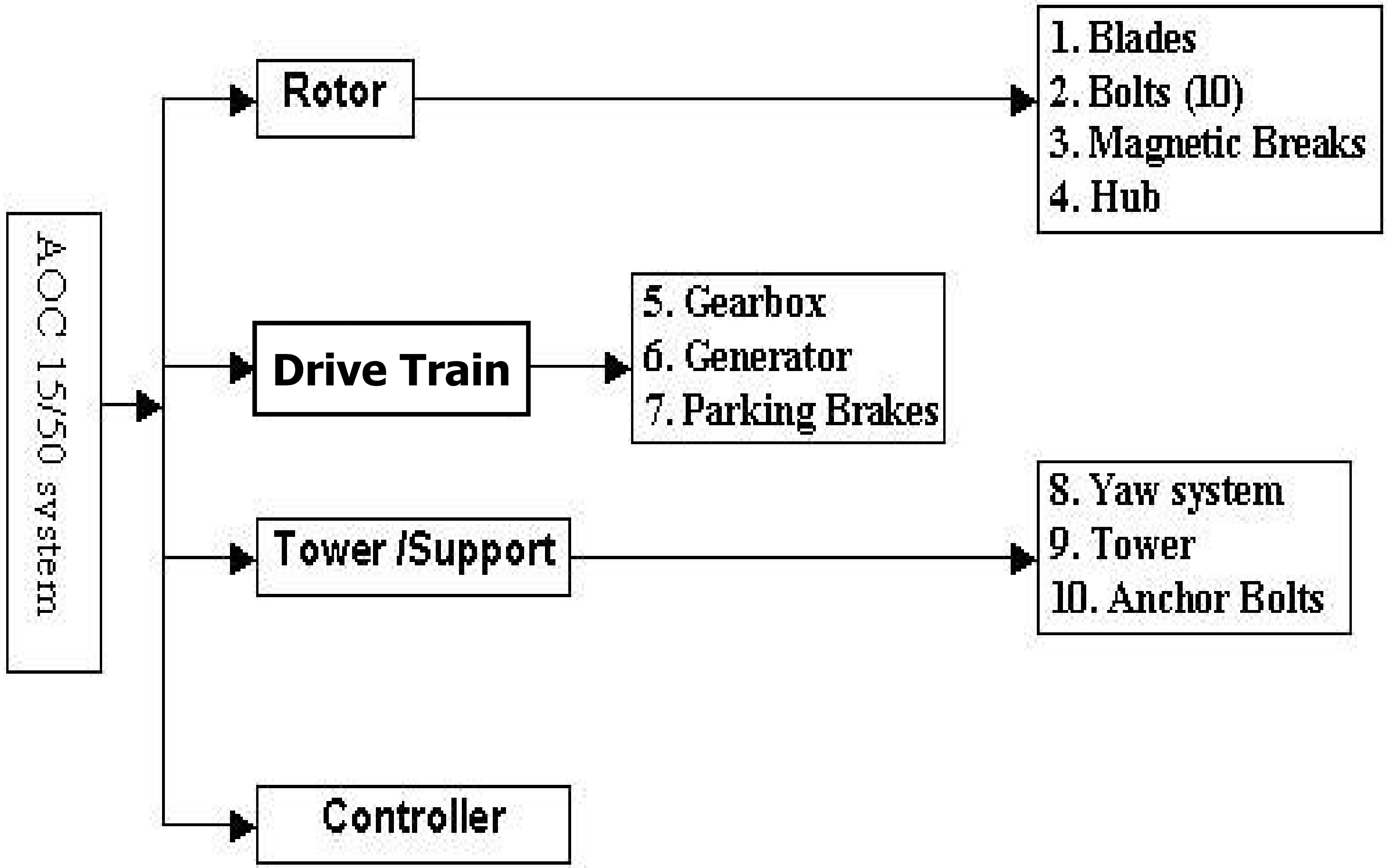
- 50 K Watt system
- Downwind , Stall regulated
- Passive yaw
- Cut-in wind speed 4.6m/s
- Cut-out wind speed 22.4m/s
- Rated power 50Kwatt @12m/s and up.



AOC 15/50 components

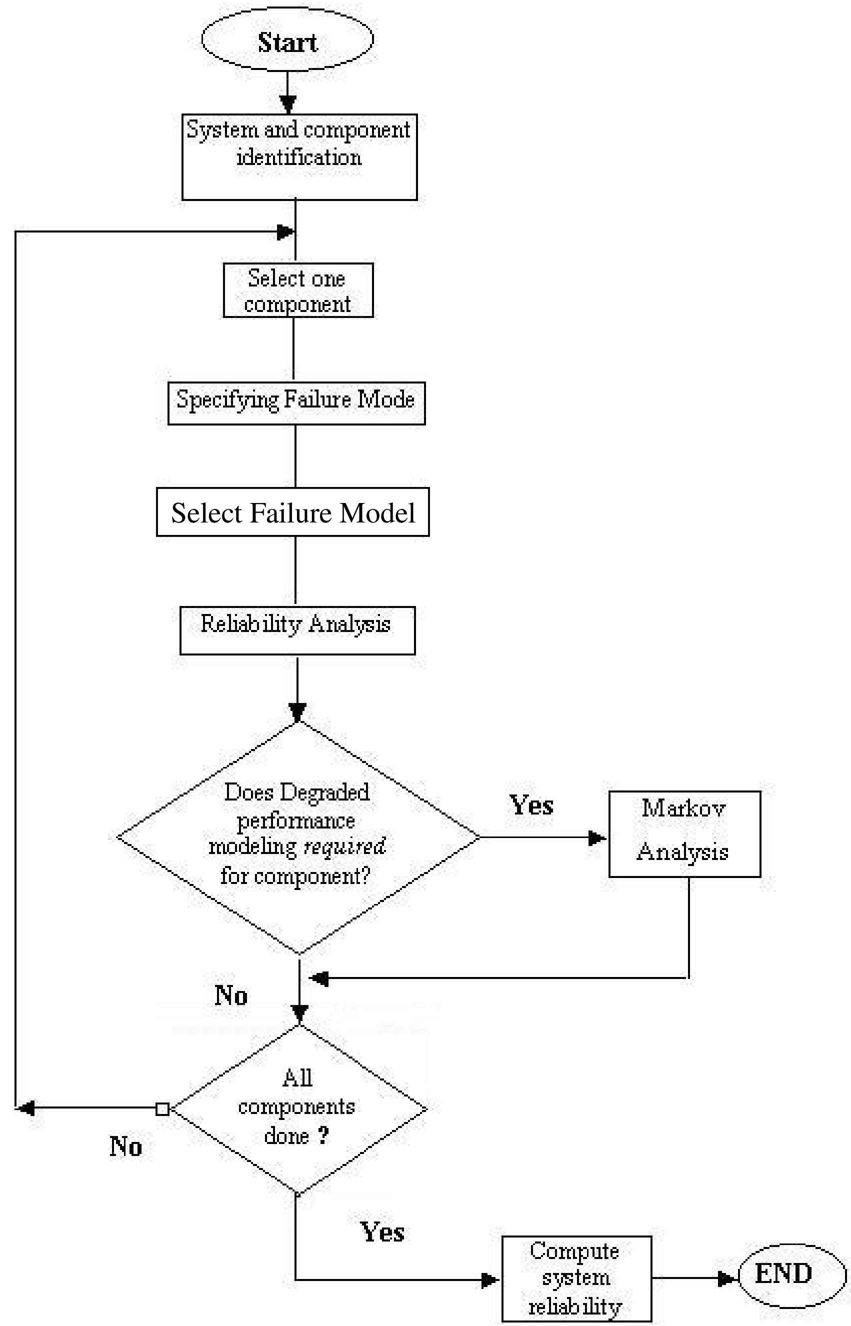


System Description and components



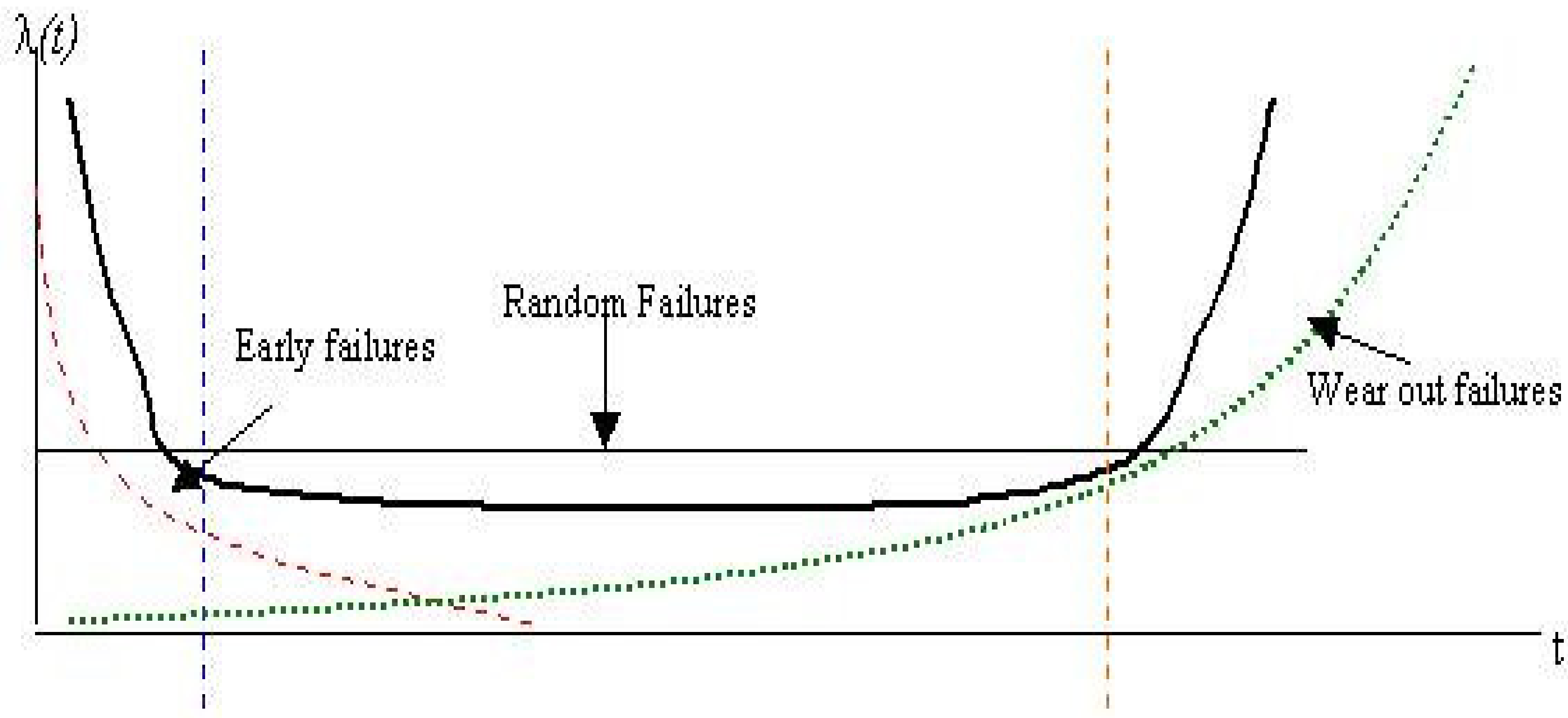
Methodology adopted for Reliability Analysis

- The steps carried out to conduct the analysis depicted in the flow chart.



Failure Modes

- Reliability Analysis require failure rate data for all components.
- FM Dependent on Working environment of component.



FMEA and Selection of Reliability Models

Components	Failure Modes	Consequences	RA Model
Blade	Fatigue	System failure	Physical Reliability Models
Hub	Fatigue	System failure	Physical Reliability Models
Bolts	Shear failure/Fatigue	2 Bolts Failed = System Failure	Physical Reliability Models
Aerodynamic Breaks	Fatigue	2 Brakes Failed = Sys Failure	Wiebull Reliability Model
Generator	Random	System Failure	Random Failure Model
Gearbox	Random	System Failure	Random Failure Model
Parking breaks	Fatigue	Unable to stop.	Wiebull Reliability Model
Yaw bearing	Fatigue	Degraded Performance	Wiebull Reliability Model
Tower	Fatigue	System failure	Physical Reliability Models
Controller	Random	System failure	Random Failure Model

- Exponential Reliability Model (Random Failures)

$$R(t) = e^{-\lambda t}$$

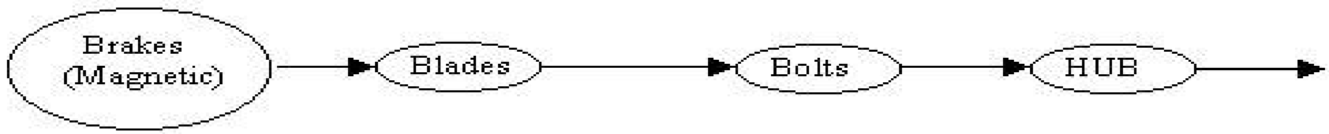
- Wiebull Reliability Model

$$R(t) = \exp -(t/\theta)^{\beta}$$

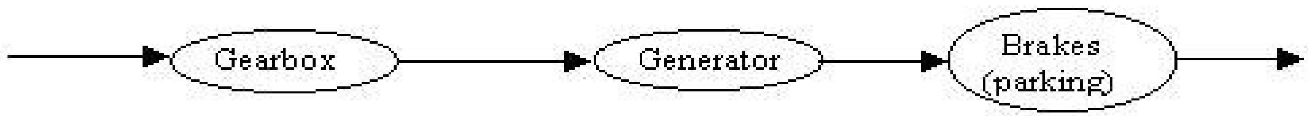
- Physical Reliability Model

Governed by Stress distribution and Strength characteristics of a component

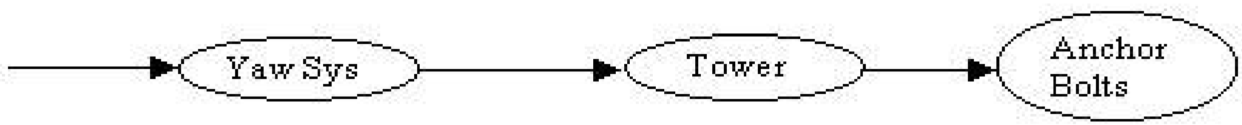
Reliability Analysis - Reliability Block diagrams



$$R_{\text{Rotor}} = R_{\text{brake-Mag}} \times R_{\text{blade}} \times R_{\text{bolts}}\, R_{\text{HUB}}$$



$$R_{\text{D\_train}} = R_{\text{Gearbox}} \times R_{\text{Generator}} \times R_{\text{Brakes Assembly}}$$



$$R_{\text{Support}} = R_{\text{Yaw\_sys}} \times R_{\text{Tower}} \times R_{\text{Anchor-Bolts}}$$

$$R_{\text{SYS}} = R_{\text{Rotor}} \times R_{\text{D\_Train}} \times R_{\text{Support}} \times R_{\text{Controller}}$$

Reliability Analysis – RANDOM FAILURES

3 – Components are Analyzed using CFR.

- Generator
- Gearbox
- PLC

Failure Rate for Generator

$\lambda(t) = 0.796 \times 10^{-6}$ / hr

R(t) = 0.997 for t = 8760 hrs (1 year)

Reliability Analysis – TIME DEPENDANT FAILURES

- 3- Component Failing due to Fatigue - Wiebull Reliability model.
- Failure data available for Yaw bearing: Data Manipulation required for Tip and Parking brake

Tip Brake:

$\lambda = 100.00 \times 10^{-6}$ /hr => MTTF = 10,000 hrs

Using Modeling Equation for Wiebull Model

$$MTTF = \theta\, \Gamma(1 + \frac{1}{\beta})$$

Reliability Analysis – TIME DEPENDANT FAILURES

- Unknown parameters – Selection of β(shape parameter) value with regards to following table.

Table for β Values (Ebeling 1997)

Values	Property
0<β<1	Decreasing Failure rate DFR
β =1	Exponential Model or Random Failures
1<β<2	***Increasing Failure rate IFR***
β=2	Linear Failure: Rayleigh Distribution Model
β>2	***Increasing Failure rate IFR***
3≤β≤4	FR Values approach Normal distribution

Reliability Analysis – TIME DEPENDANT FAILURES

- β = 1.85 for Tip breaks.
- θ = 11260 Hrs

$$\text{MTTF} = \theta\, \Gamma\left(1 + \frac{1}{\beta}\right)$$

R(t) = 0.5334 @ t = 8760 hours

Similar approach is used to determine the Reliability for Parking Brakes with β = 2.2

Reliability Analysis – Physical Reliability Models

- Blades, Bolts, HUB.

- Involve Two main Step.

  1. Static Modeling.
  2. Dynamic Modeling.

- Static Model – specifying the failure mechanics , Structure type.

- Many model available – here used CONSTANT Strength and RANDOM Stress Model.

Reliability Analysis – Physical Reliability Models

Blades.

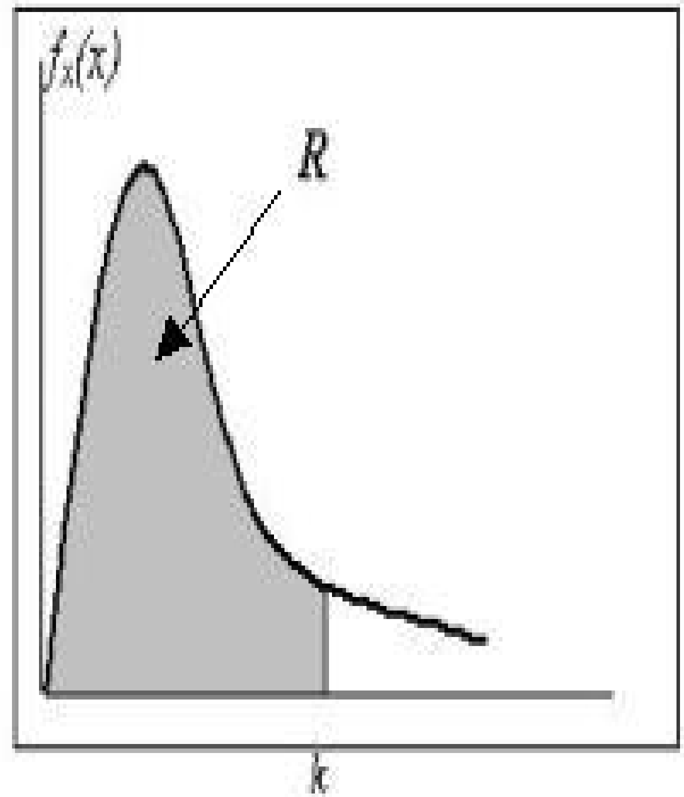
$$R = \text{ø}\left(\frac{1}{s}\,\text{Ln}\,\frac{k}{x_{med}}\right)$$

s= shape parameter for lognormal stress distribution taken to 0.1

k = Strength of Material

$x_{mode} = x_{med}/\exp(s^2)$

x_{mode} = *Maximum Stress*



Reliability Analysis – Physical Reliability Models

- Stress on Blade Root

$$T = C_T \tfrac{1}{2} \rho \pi R^2 U^2$$ (Manwell 2002)

$$M_\beta = \frac{1}{B}\int_0^R r[1/2\, \rho\pi\, 8/9 U^2\, 2r]\, dr$$ (Manwell 2002)

$$M_\beta = R \frac{2T}{3B}$$

$$\sigma_{max} = M_\beta \frac{C}{I_b}$$

Reliability Analysis – Physical Reliability Models
Static and Dynamic Modeling

- $R = \phi\left(\frac{1}{s} \text{ Ln } \frac{k}{x_{med}}\right)$

For Dynamic Reliability (Periodic Loading)

- $R = \exp^{-(1-R)\,\alpha\, t}$ (Ebeling 1997)

Loading Model for WT Blades (Manwell 2002)

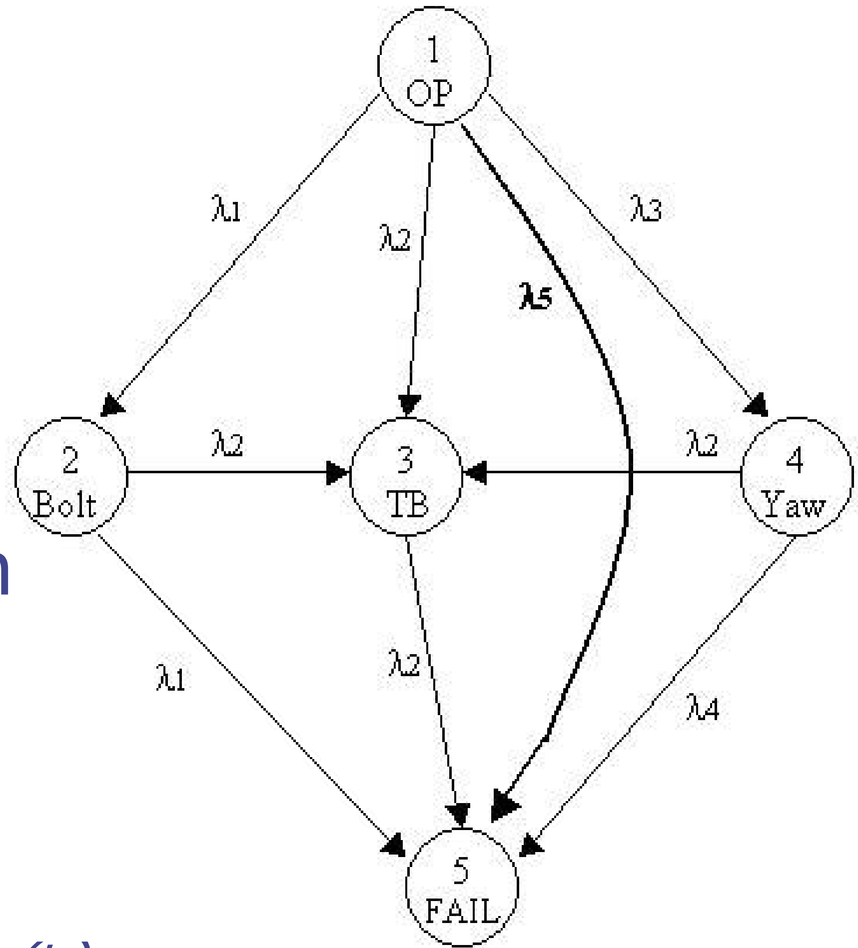
$\eta_L = 60\, K\, \boldsymbol{n}_{rotor}\, H_{op}\, Y$

$\mathbf{R}_{blade} = 0.9068$

Similar Procedure : Bolts, Hub & Anchor Bolts

Markov Analysis

- Markov model predict on basis of reliability data how likely the system is going to be in a certain state.



Standard Markov Equation

$P_1(t) = e^{-(\lambda 1 + \lambda 2 + \lambda 3 + \lambda 5)t}$

$P_2(t) = e^{-(\lambda 1 + \lambda 2)t} - e^{-(2\lambda 1 + \lambda 2)t}$

$P_3(t) = e^{-\lambda 2 t} - e^{-(4\lambda 2)t}$

$P_4(t) = e^{-(\lambda 4 + \lambda 2)t} - e^{-(\lambda 3 + \lambda 4 + \lambda 2)t}$

$\mathbf{P_5(t)} = 1 - P_2(t) - P_3(t) - P_4(t) - P_1(t)$

Markov Analysis

On the basis of model we have the individual probabilities of being in every state.

S.No	State of System	Probability @ t = 8760	Probability @ t = 8076 x2
1	P_1 (t)	0.3326	0.1106
2	P_2 (t)	0.035	0.0024
3	P_3 (t)	0.3868	0.1725
4	P_4 (t)	0.0395	0.309
5	P_5 (t)	0.2066	0.68294

Fault Tree Analysis

Probability of Top Event P(T) = System Failure

$P(T) = F_{rotor} \cup F_{controller} \cup F_{derive\ train} \cup F_{tower\ suppor}$

$P(T) = [F_{blades} \cup F_{bolts} \cup F_{Hub} \cup F_{tipbrk}] \cup [F_{Controller}] \cup [F_{generator} \cup F_{gearbox} \cup F_{parkingbrk}] \cup [F_{yaw} \cup F_{tower}]$

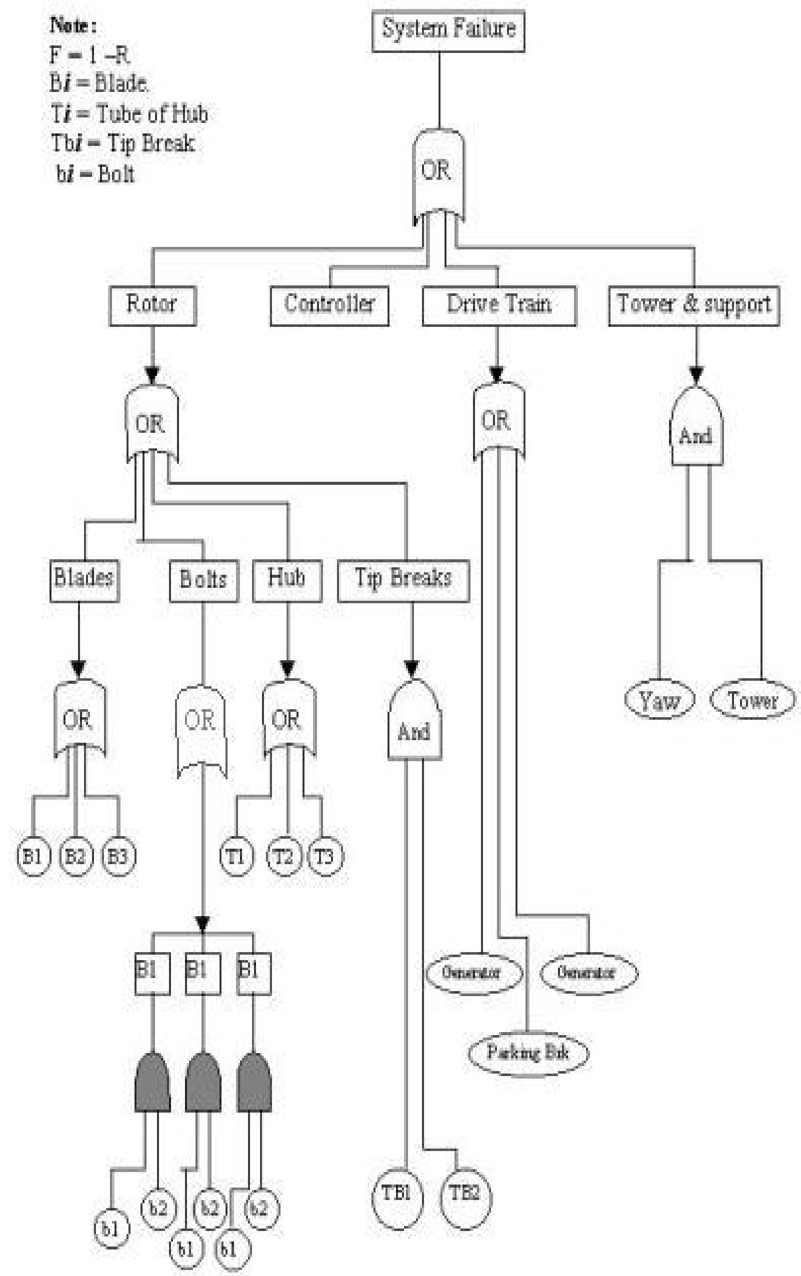
$P(T) = 0.6427$

$R(T) = 1 – P(T)$

$R(T) = 0.3573$

Markov Analysis

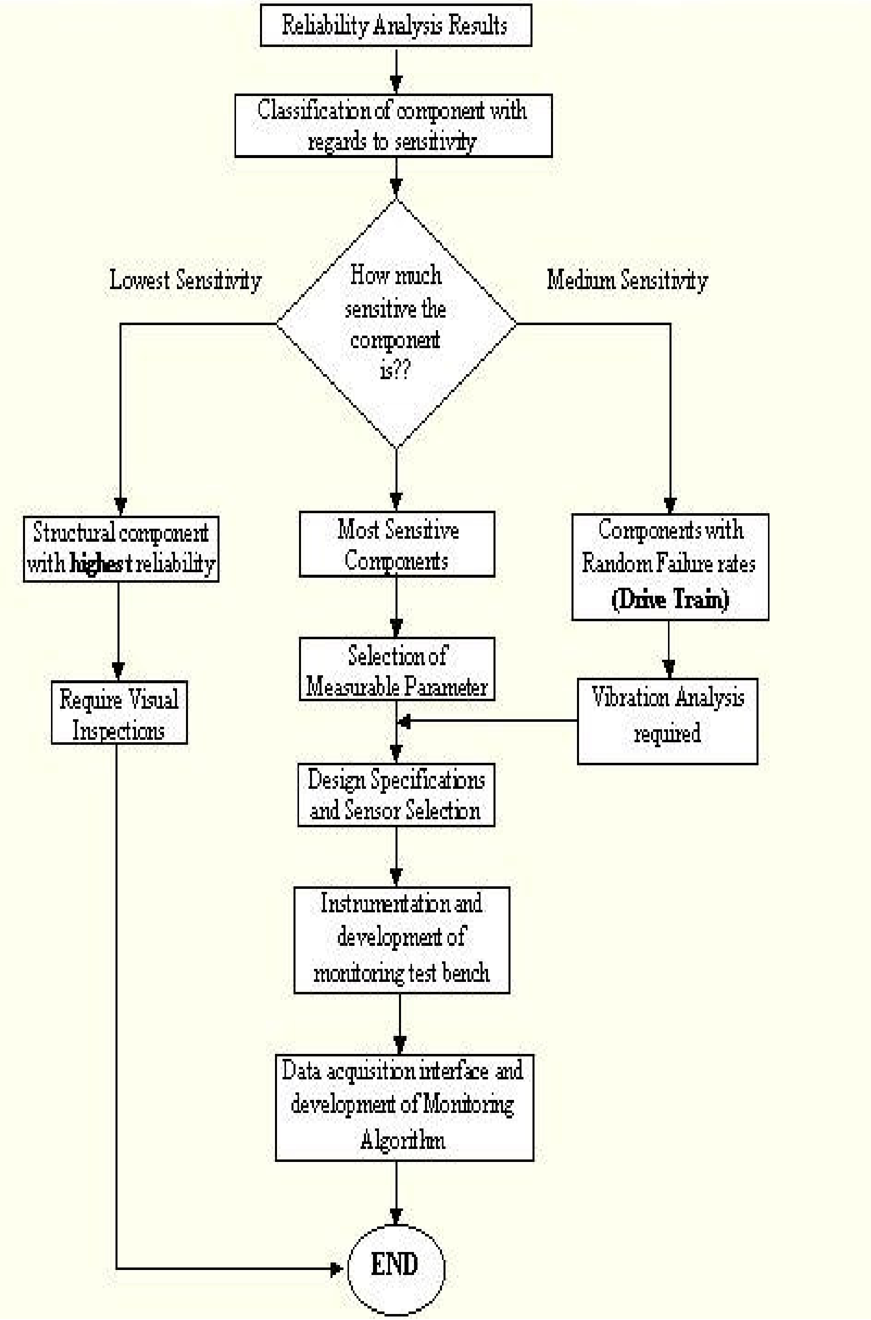
33.26% availability in first year of installation the results for both are fairly close



Reliability Analysis Result and Identification of Problematic Components

Component	Reliability	Failure rates
Tip Brake	R = 0.53340	**1.00×10^{-4}**
Yaw Bearing	R = 0.90130	**0.115×10^{-4}**
Generator	R = 0.99305	0.769×10^{-6}
Gearbox	R = 0.99440	0.63×10^{-6}
Parking Brake	R = 0.9990	2.16×10^{-6}
Blades	R = 0.90680	1.116×10^{-5}
Bolts	R = 0.90680	1.116×10^{-5}
Hub	R = 0.90680	1.116×10^{-5}
Tower and Anchor Bolts	R = 0.99970	1.000×10^{-7}

Adopted Methodology for CM System Design



Parameter Selection for components

Component	Sensitivity	Selected Parameter
1. Tip Brakes	Highly Sensitive – Wear out Effects	**Current Sensing**
2. Yaw bearing	Highly Sensitive – Wear out Effects	**Strain Measurement**
3. Generator	Random Failure – Low sensitivity	**Vibration Monitoring**
4. Gearbox	Random Failure – Low sensitivity	**Vibration Monitoring**
5.Parking Brake	Wear out but longer life	Visual inspection
6. Blades	Structural component	Visual inspection
7. Bolts	Structural component	Visual inspection
8. Hub	Structural component	Visual inspection
9. Tower and Anchor Bolts	Structural component	Visual inspection

Experimentation and Analysis for CM system Design

- Some Experimentation and Analysis was performed before proceeding toward the system design
- An Inherent Imbalance of Mass was observed on the Derive Train

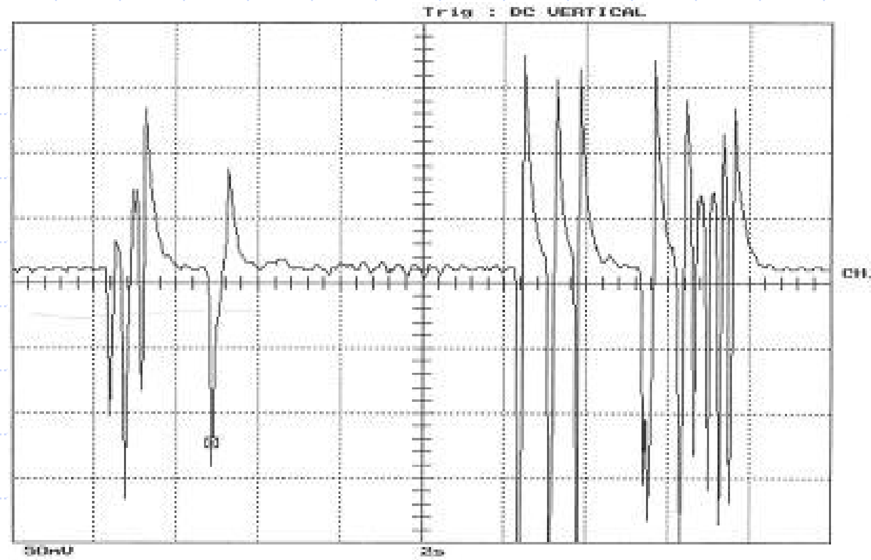
$\varepsilon = 9.65 \times 10^{-7}$ m/m

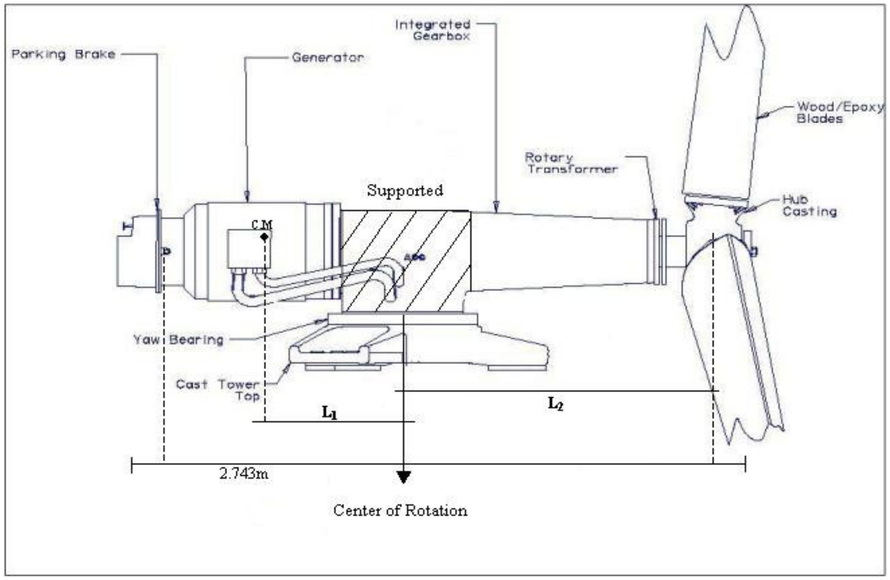
Δ**R = ε. (GF) .R**

Δ**R** = 0.009118 Ω

ΔV ∝ ΔR

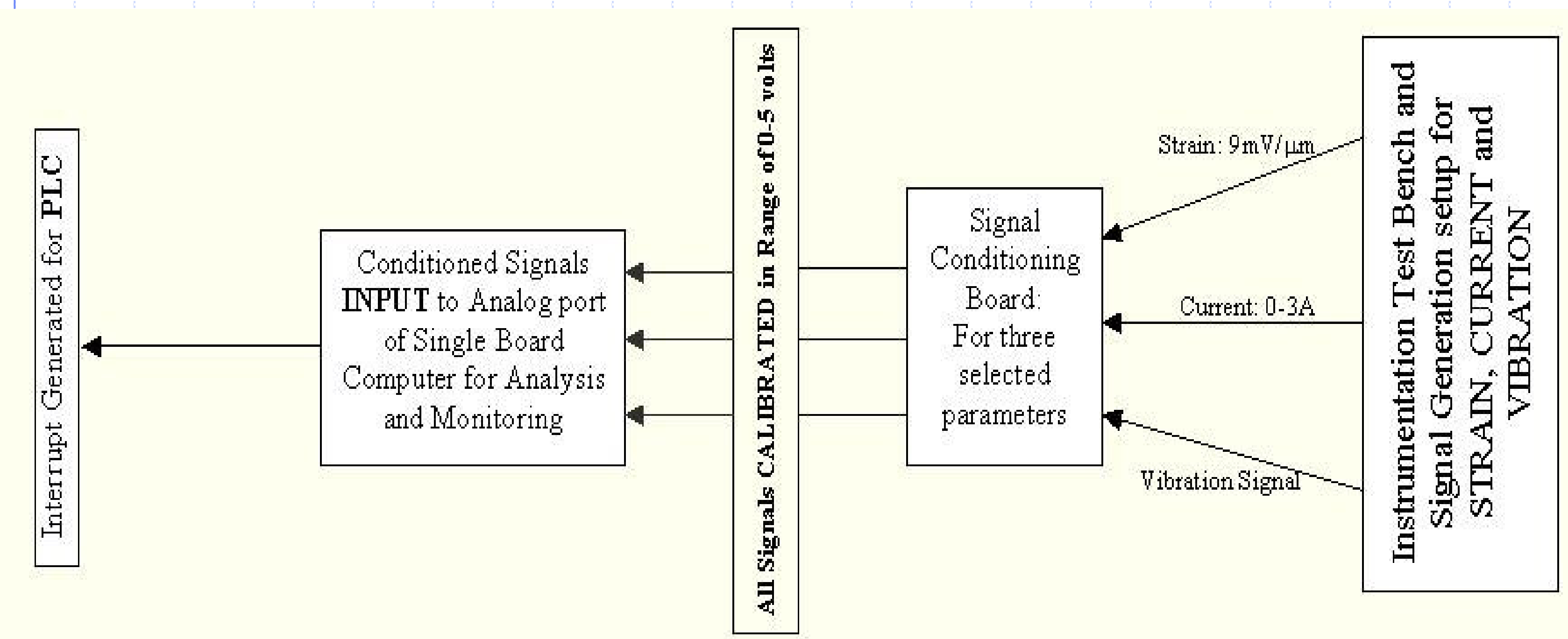
- Vibration Monitoring – Drive Train





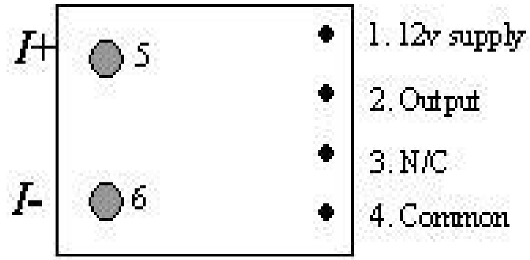
Proposed CM system Block Diagram

- The Proposed CM setup(Test Bench) will be able to provide Signals for three parameters strain, current and vibration.
- The System: Electronic interfaces & Independent SBC



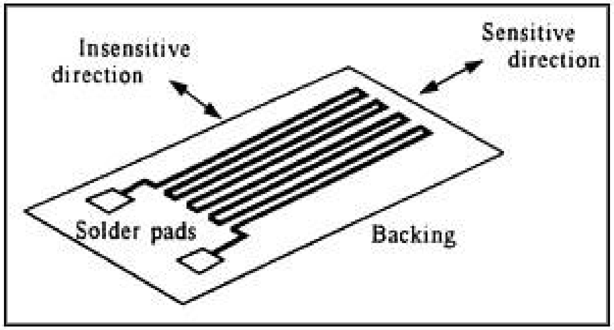
Sensors Selection (Current – Tip Brake)

- Power Supply- Tip brake: 0-5A/120VAC
- Sensor Detecting Range.
- Dynamic Operation Range in Harsh Environments
- SCD05PUN – CUI Inc

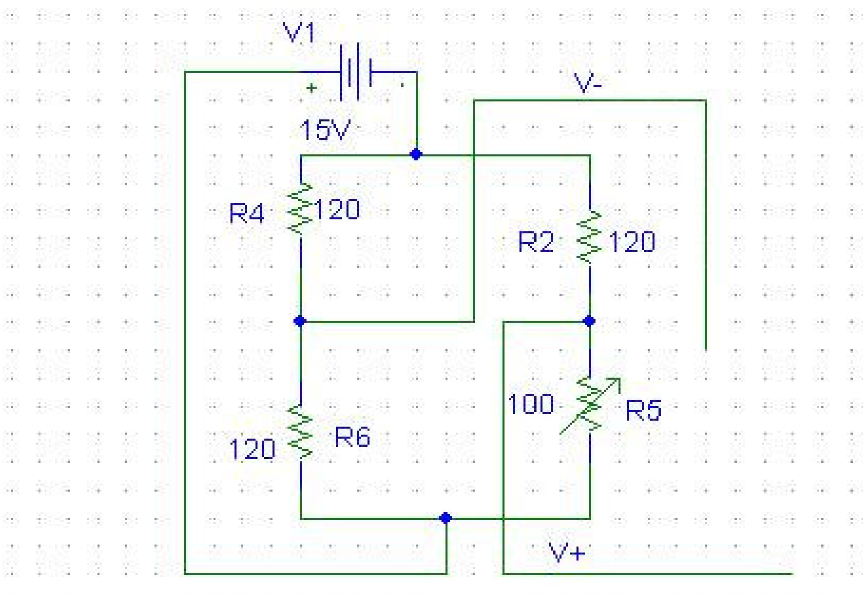


Sensors Selection (Strain – Yaw Bearing)

- Metal Strain Gauge



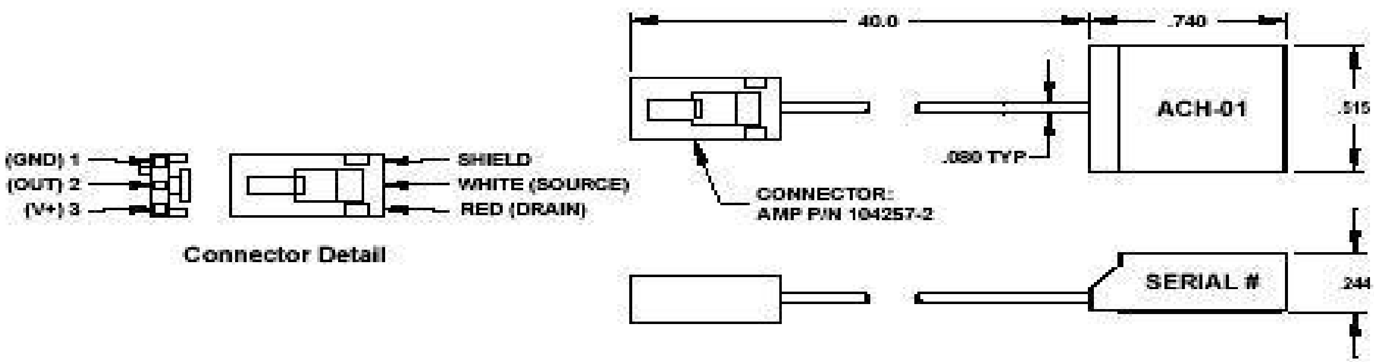
- Bridge Configuration
- Half Bridge configuration



- GF = 2.0; R = 120Ω
- Two Gauges provide Temperature Compensation

Sensors Selection (Vibration Analysis)

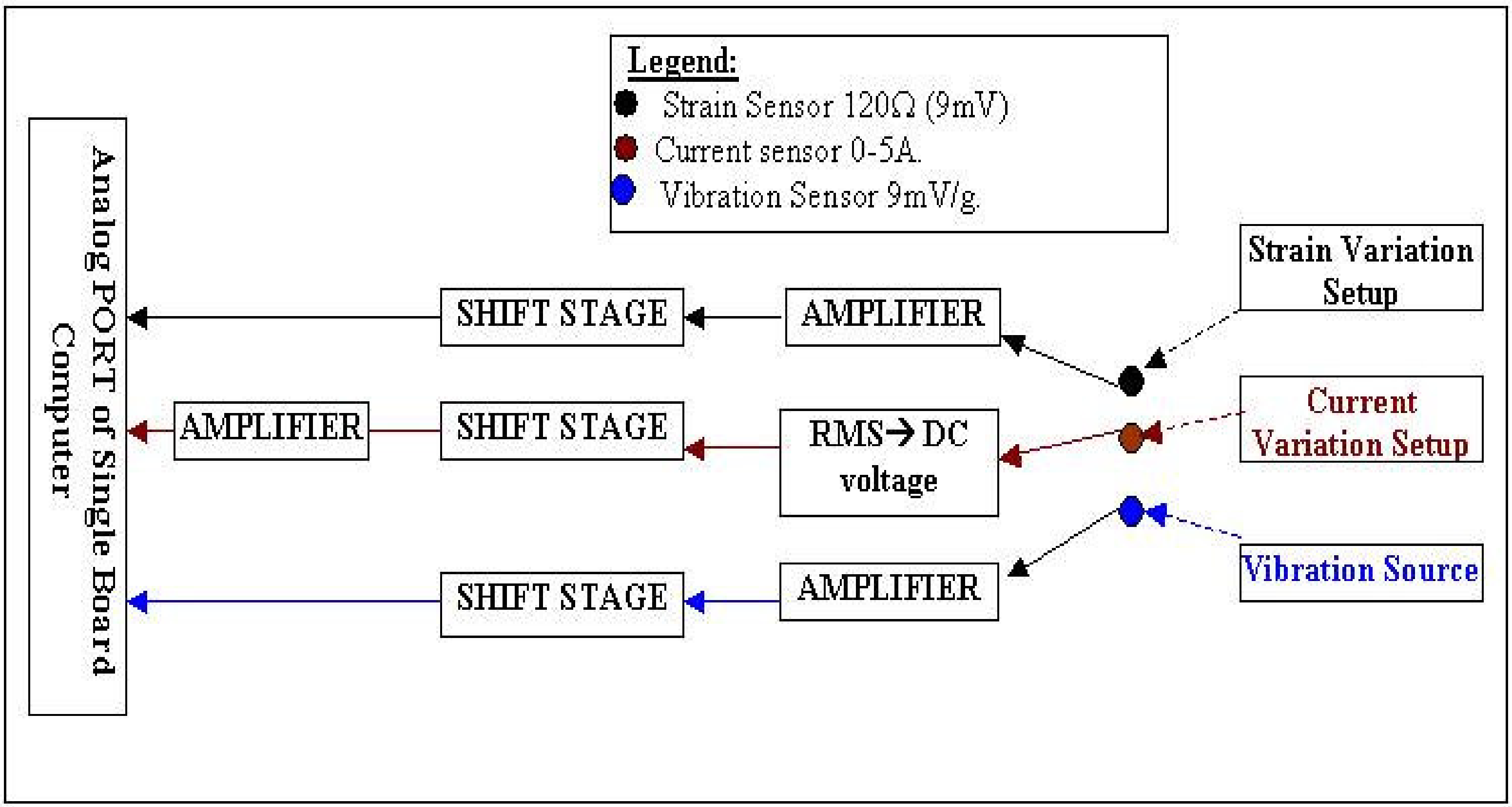
- Piezoelectric sensors are typically used.
- Sensor Detecting Range (Frequency).
- Dynamic Operation Range in Harsh Environments
- ACH-01: Manufactured "Measurement Specialist Ltd"



ACH-01-03 with Shielded Cable

Layout Design of Instrumentation Board

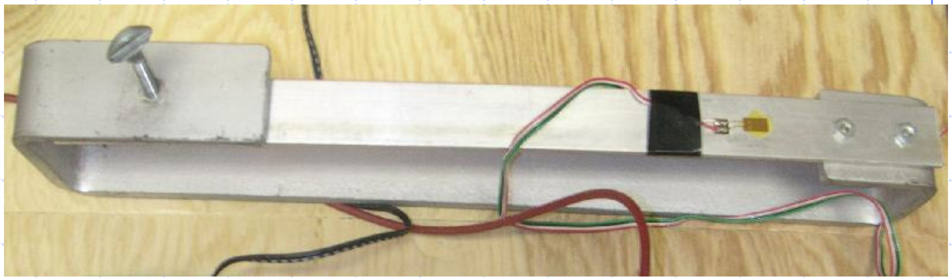
- Based on Selected Sensor the following Layout was designed to capture the signals and Acquire Data for analysis and Monitoring.



Test Bench Setup

- Signals Source – Test Bench Setup for three parameters

Strain Variation Setup

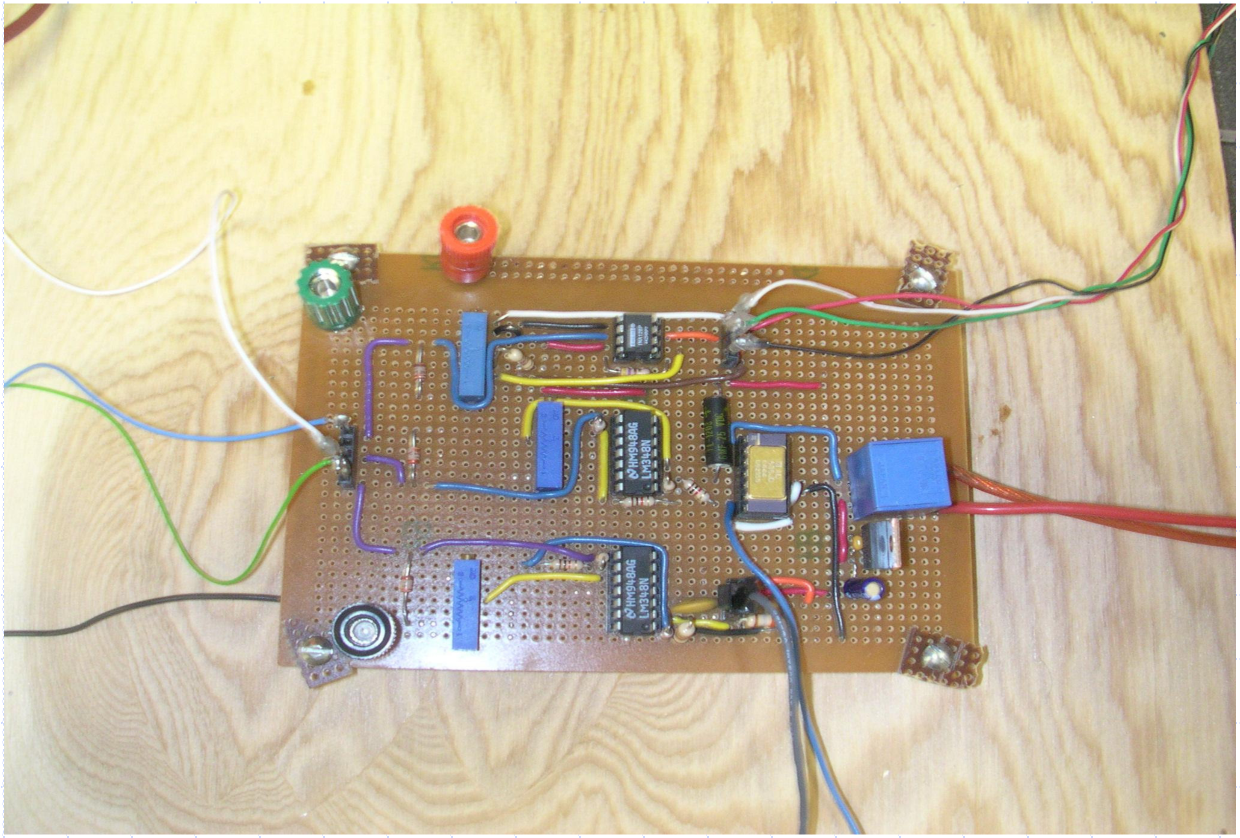


Current Variation Setup

Vibration Signal source

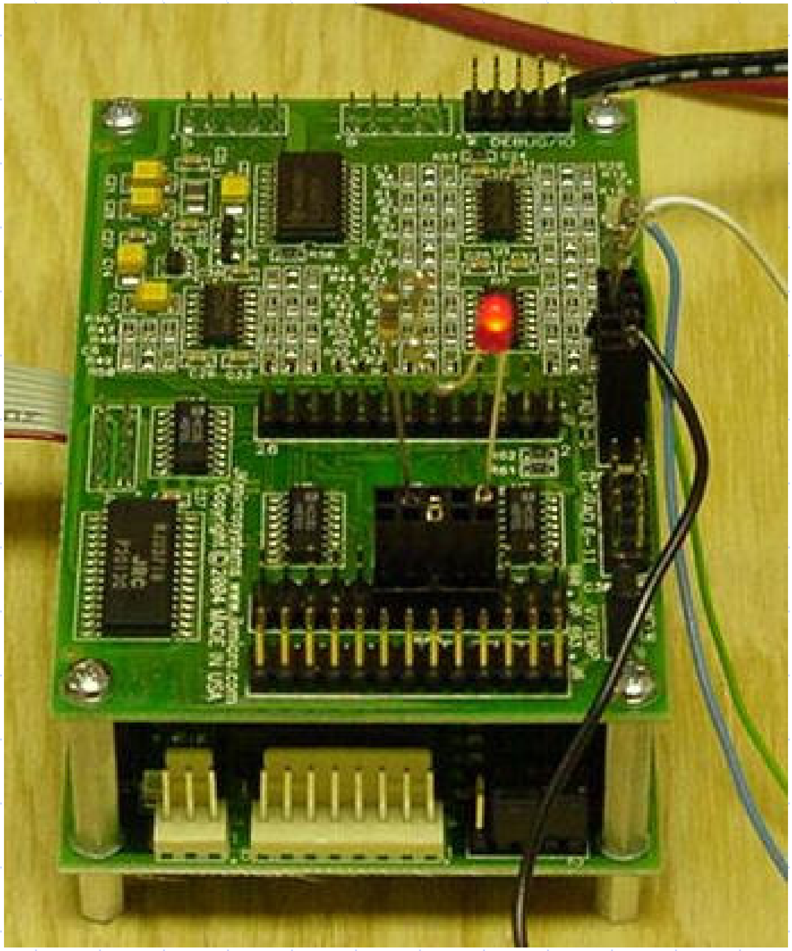
Designed Instrumentation Board

- Board Operate at supply of ± 15 volts DC
- Separate on board supply setup for Current Sensor
- Output signal protection for analog channels



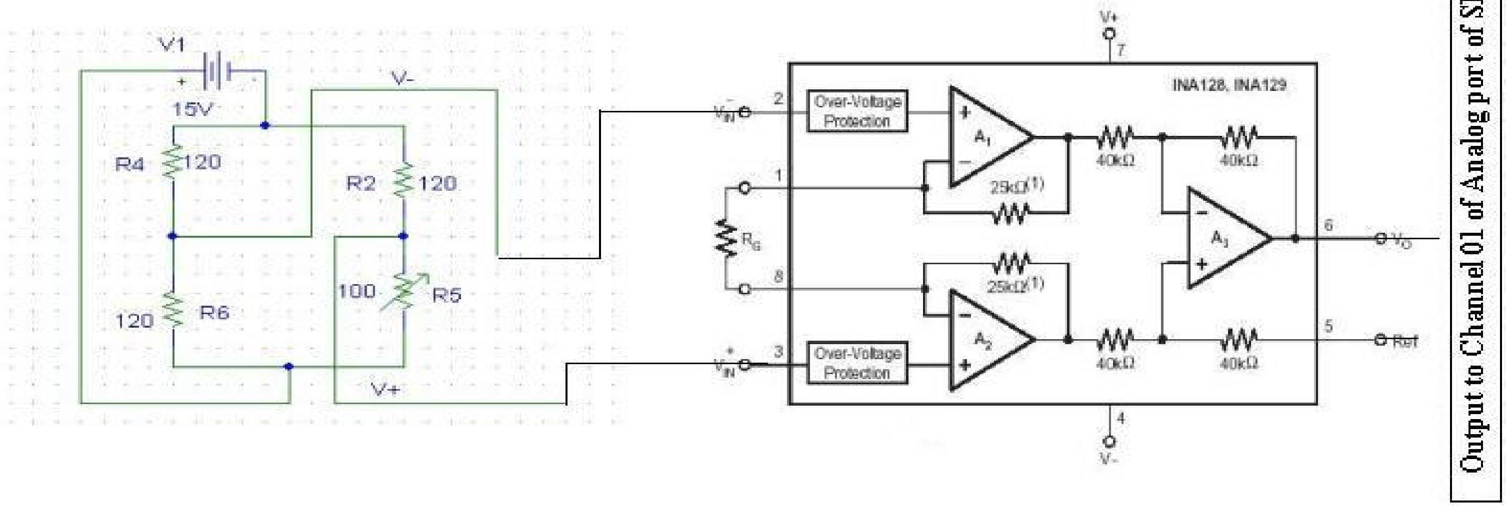
Single Board Computer (SBC)

- JK-micro system Pico Flash digital board
- Pico Flash – Pico I/O analog expansion
- Equivalent to Intel 186 processor
- Built in Dos Env.
- C and C++ lib
- 12 bit 11 analog channel and 2 digital ports for output and input
- Interfaced with LAPTOP using HyperTerminal



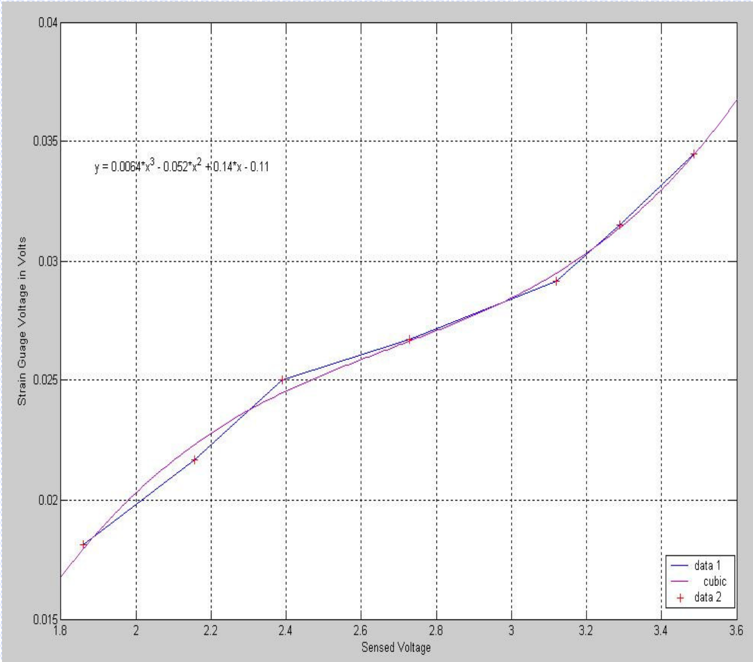
Signal conditioning and Calibration - Strain

Strain Instrumentation Circuit

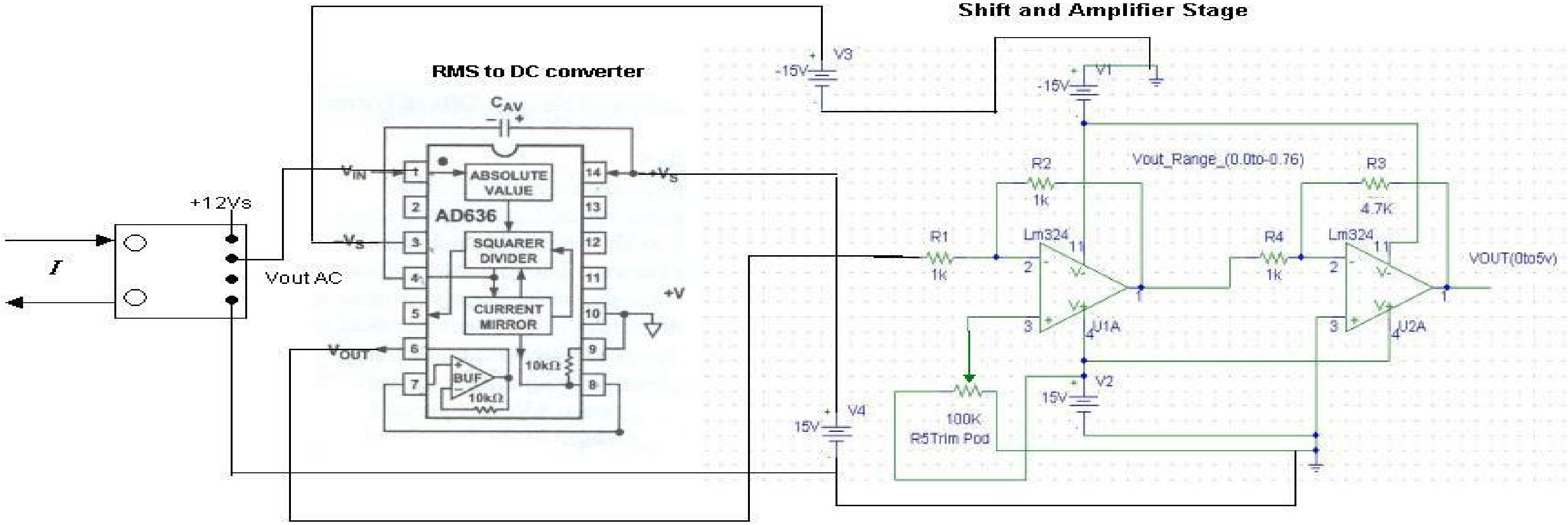


- Input Strain Vs Output Voltage
- DC – offset

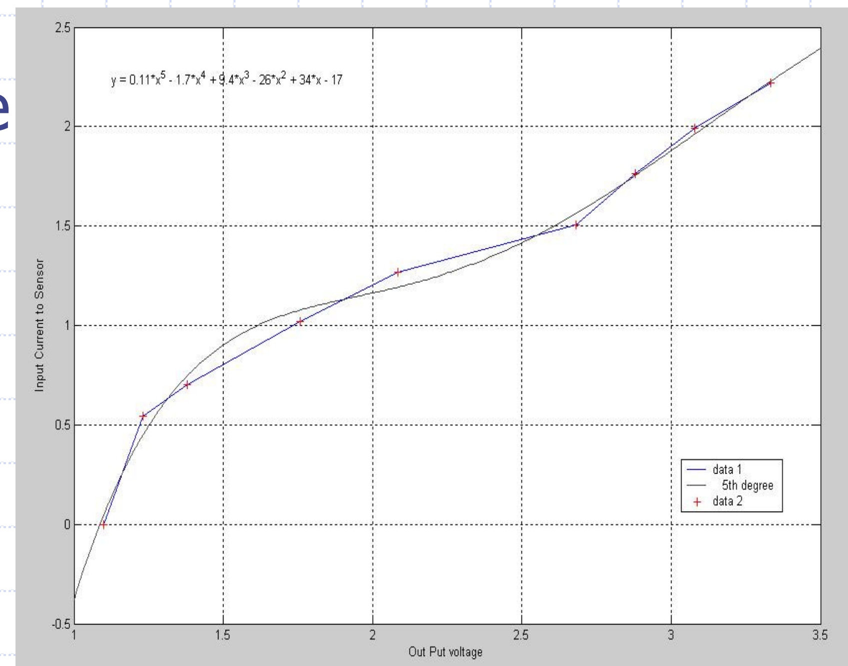
Y (strain) = 0.0064 x³ – 0.052 x² + 0.14 x – 0.11



Signal conditioning and Calibration - Current



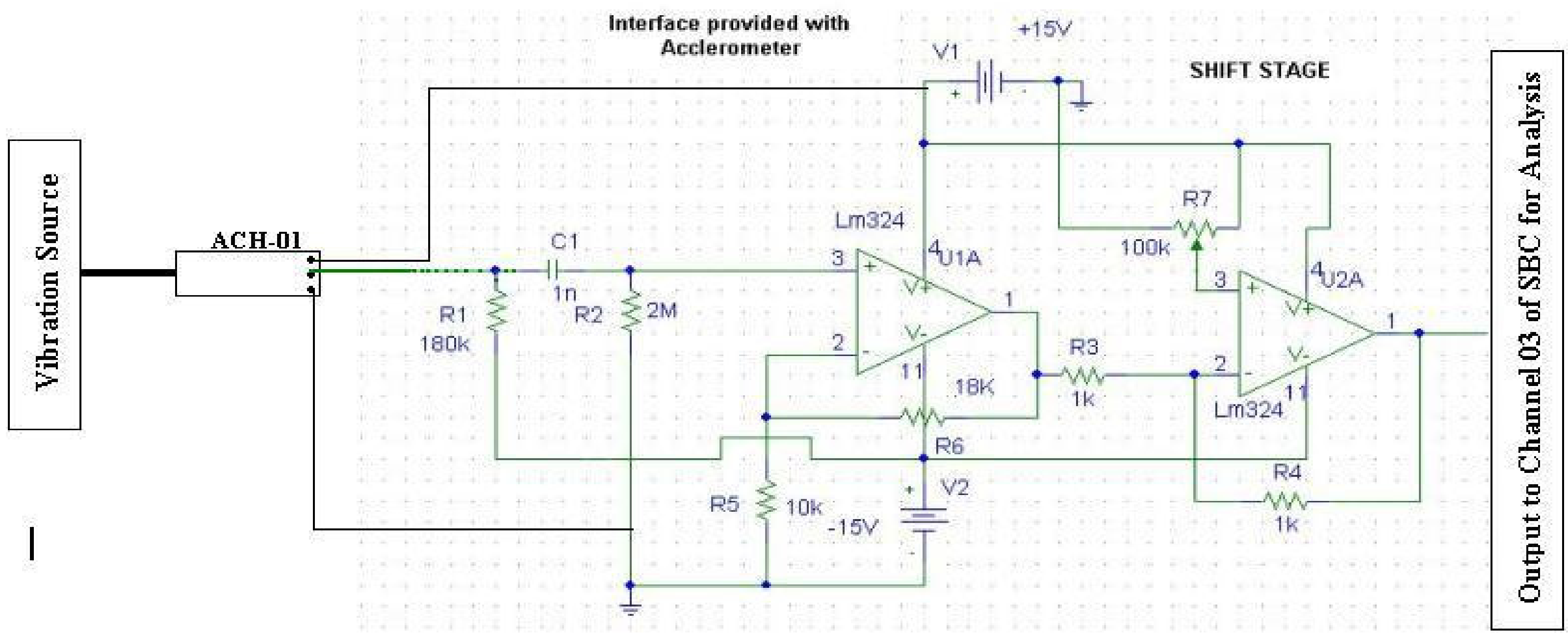
- Input Current Vs Output Voltage



- DC – offset

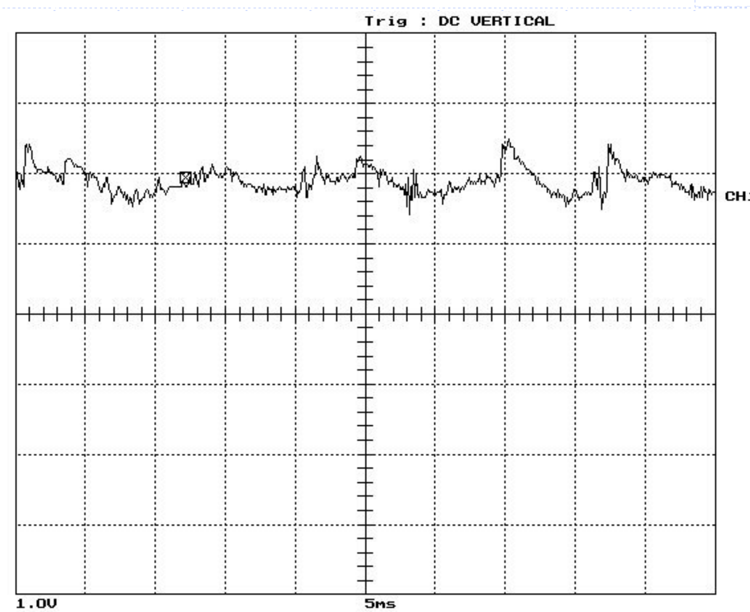
Y (current) = $0.112x^5 - 1.656x^4 + 9.432x^3 - 25.72x^2 + 34.05x - 16.28$

Interface and Calibration - Vibration



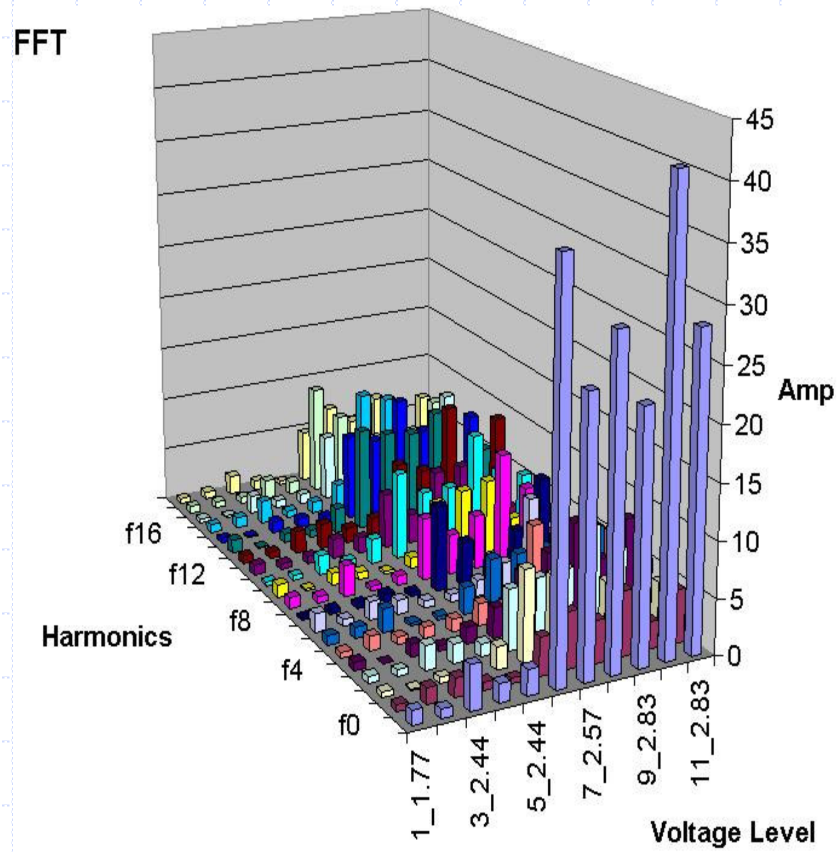
- Interface provided with datasheet

- DC – offset for complete signal capture



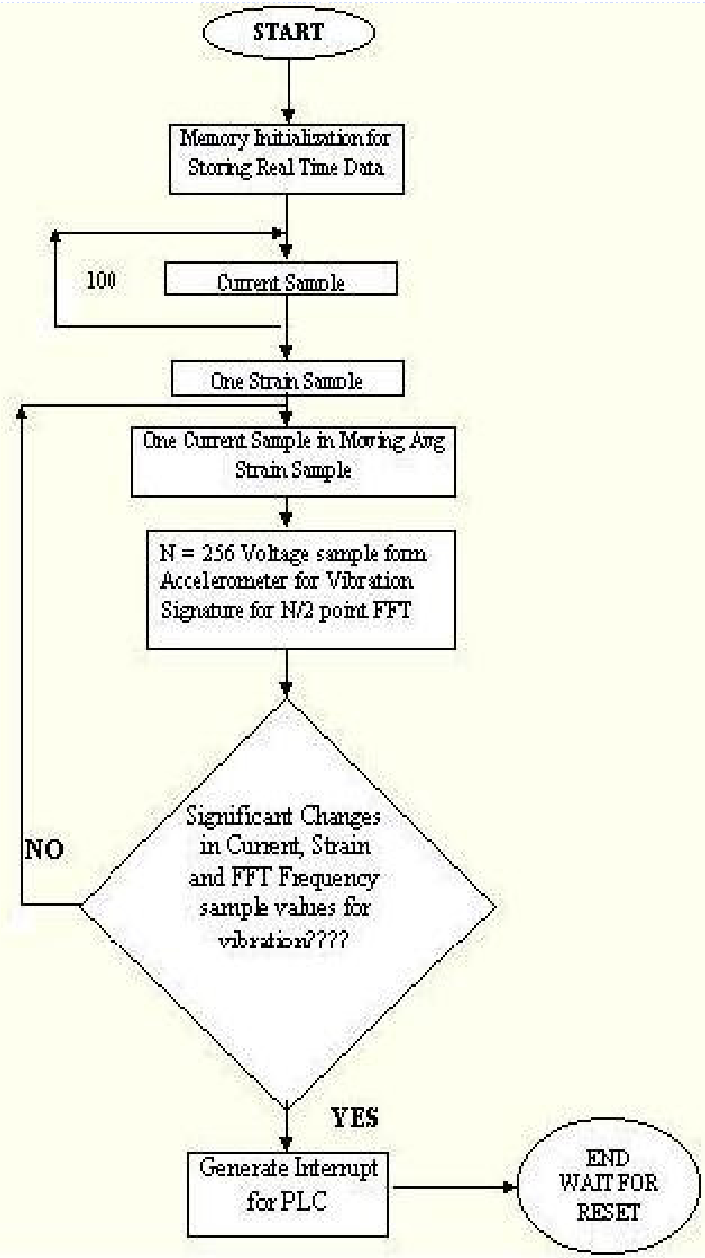
Vibration Analysis and FFT result

- DFT is required
- DFT computation takes N^2 multiplication and N(N-1) additions to compute
- Smart FFT computation routine – Butterfly algorithm
- Routine adopted from Literature
- Total computation << 1 sec for N = 256 sample window



Condition Monitoring Routine

- Routine written in C++
- Moving Average window for Current samples
- Instantaneous Strain Sampling
- FFT computation for N/2 frequency harmonics
- Interrupt for PLC



Concluding Remarks

Reliability Analysis for AOC15/50- Design of LOW cost CM system

- Reliability Analysis similar to result of other researchers
- Life time Vs Environment
- Unavailability of Failure data related to Wind Engineering
- System is less then 50% reliable/Available

- CM system design based on RA: Different Failure data may suggest a different design
- CM system may perform differently when mounted on AOC15/50
- Voltage Drift in Current Sensor
- SBC capable of handling more parameters
- Vibration analysis: Average magnitude of spectrum

Recommendations for Improvement

- Precise Wind Turbine part data.
- Further Detailed Reliability Analysis

- Field Test for CM system
- LAN capabilities of SBC
- Improved Current Sensor is required
- 4 setups of strain
- Detailed in vibration analysis
- FFT Range and Resolution

Thanks And Acknowledgements

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- Friends

Questions/ Discussion