ITN ENERGY-SMARTOPS WORKSHOP "Optimization to provide energy savings by better integration of operations across the process-mechanical-electrical interfaces", LADENBURG, GERMANY, 22-24 Oct 2013.

MARIE CURIE ACTIONS

Energy-SmartOps

Integrated Control and Operation of Process, Rotating Machinery and Electrical Equipment

MULTIVARIATE STATISTICAL PROCESS MONITORING

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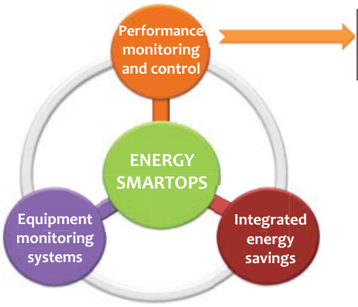
1. My Project in SmartOps

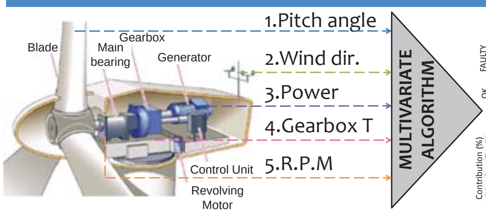


To devise new algorithms for overall performance monitoring and control.

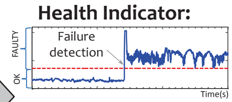
WORK PACKAGE 3: MAINTENANCE AND DIAGNOSIS

ESR-D	ESR-H	ESR-I
Multivariate statistical process predictive monitoring using operational data.	Interconnections between process, mechanical and electrical equipment.	Reactive performance-based maintenance planning for process plants.

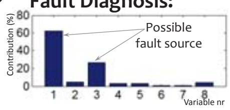
2. Problem Statement



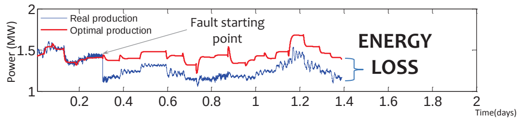
Health Indicator:



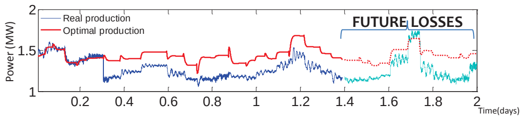
Fault Diagnosis:



Performance degradation:



Prediction of fault evolution:



3.1 Methodology: Canonical Variate Analysis

- **Data driven:** Not based on first principle equations.
- **Multivariate:** Takes into account correlation between variables.
- **Dimensionality reduction:** Selection of the most relevant information.
- **Fault detection:** A scalar statistic (Q, T^2) can characterize multi-dimensional data variability.

✓**Dynamic:** Time correlation.
✓**State-space based:** More suitable for dynamic monitoring.
✓**System identification:** By linear regression using process data.
✓**Nonlinearities:** Estimation of actual probability density functions through kernel density estimations.

Mathematical Procedure:

$$[y_1, y_2, y_3, y_4, y_5, y_6, y_7, y_8, y_9, y_{10}, \dots y_n]$$

Time k

$$y_{p,k} = \begin{bmatrix} y_k \\ y_{k-1} \\ \vdots \\ y_{k-p+1} \end{bmatrix} \qquad y_{f,k} = \begin{bmatrix} y_{k+1} \\ y_{k+2} \\ \vdots \\ y_{k+f} \end{bmatrix}$$

Covariance Matrices:

$$\Sigma_{pp} = \frac{1}{M-1} Y_p Y_p^T \quad \Sigma_{ff} = \frac{1}{M-1} Y_f Y_f^T \quad \Sigma_{fp} = \frac{1}{M-1} Y_f Y_p^T$$

Hankel Matrix:

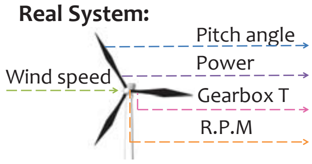
$$H = \Sigma_{ff}^{-1/2} \Sigma_{pf} \Sigma_{pp}^{-1/2} = UDV^T \quad \begin{cases} UU^T = VV^T = I \\ D_{i,j} = 0 \text{ if } (i \neq j) \end{cases}$$

Canonical variates and indicator:

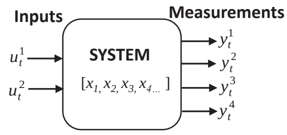
$$\underset{r \times m \cdot p}{J} = V_r^T \Sigma_{pp}^{-1/2} \qquad z = J \cdot Y_p \qquad T_j^2 = \sum_{i=1}^{i=r} z_{i,j}^2$$

3.2. CVA for System Identification

Real System:



Mathematical model:

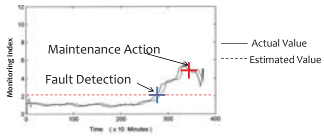


Linear state-space model:

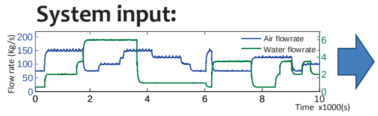
$$\begin{cases} x_{t+1} = \Phi x_t + G u_t + w_t \\ y_t = H x_t + A u_t + B w_t + v_t \end{cases}$$

$$m_t = J y_{p,t}$$

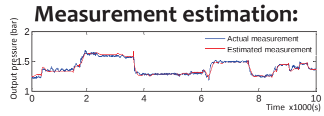
$$\begin{pmatrix} \Phi & G \\ H & A \end{pmatrix} = \mathrm{cov}\left[\begin{pmatrix} m_{t+1} \\ y_t \end{pmatrix}, \begin{pmatrix} m_t \\ y_t \end{pmatrix}\right] \cdot \mathrm{cov}^{-1}\left[\begin{pmatrix} m_t \\ y_t \end{pmatrix}, \begin{pmatrix} m_t \\ y_t \end{pmatrix}\right]$$



System input:

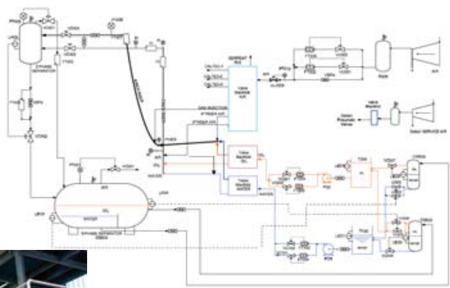


Measurement estimation:



4. Model Validation: Experimental Data

Experimental **data was acquired** in the 3 phase test rig at Cranfield University. Real **faults were introduced** in the system to obtain performance data under faulty conditions.

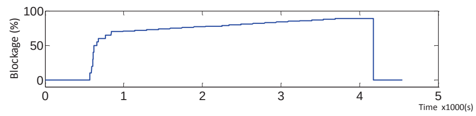


3 phase flow facility:

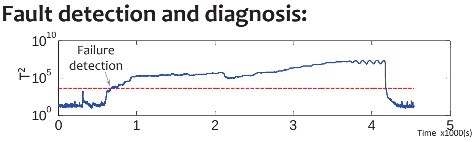
- **4" Flow loop** (55 m long 2° inclined pipeline, 10.5m catenary shaped riser)
- Maximum pressure: **7 barg**
- Air supply: Up to **1410 m³/hr** @ 7 barg
- Water supply: Up to **100 m³/hr** @ 10 barg
- Controlled by **Delta V**

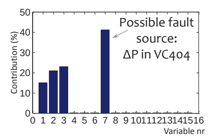
5. Results (Blockage in top separator intake)

Fault evolution:

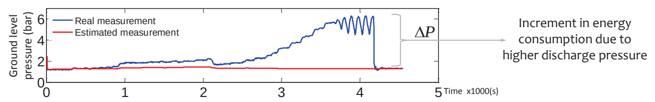


Fault detection and diagnosis:





Energy waste estimation:



$$\Delta E = E_F - E_N = \int_0^T {}^w\dot{m}\left(\frac{gH_F}{{}^w\eta_F} - \frac{gH_N}{{}^w\eta_N}\right) + {}^a\dot{m}\left(\frac{C_p T_1}{{}^a\eta_F}\left[\left(\frac{P_{2F}}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] - \frac{C_p T_1}{{}^a\eta_N}\left[\left(\frac{P_{2N}}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right) dt$$

Cranfield UNIVERSITY ABB energy smartOps

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