Remaining Useful Life Control of a Deteriorating Wind Turbine with Flexible-shaft Drive-train

Mônica S. Félix[a] John J. Martinez[a] Christophe Bérenguer[a]

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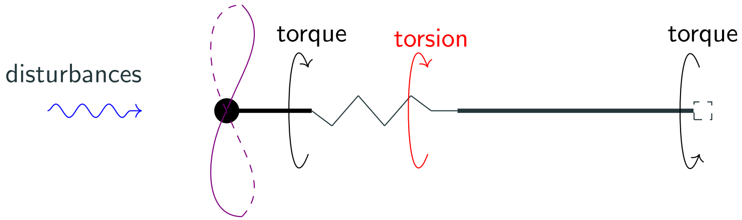
Motivation



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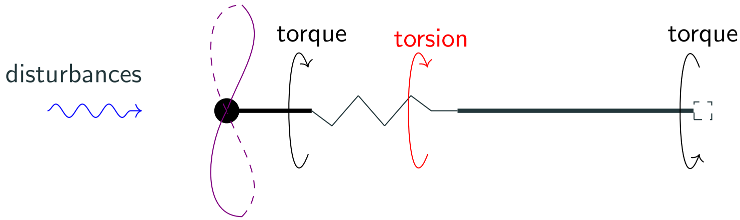

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- Stress $\rightarrow$ degradation $\rightarrow$ downtime/maintenance.

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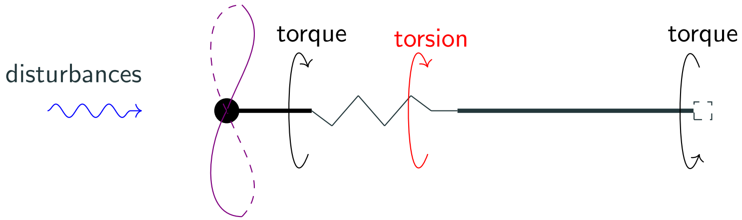

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- This work presents a health(degradation)-aware control solution (focused on RUL control).

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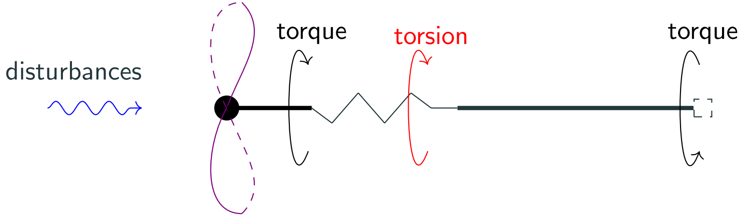


Figure 1: *Torsion caused by intensity of turbulence*

- System suffers from stress during operation often neglected.
- Stress $\rightarrow$ degradation $\rightarrow$ downtime/maintenance.
- This work presents a health(degradation)-aware control solution (focused on RUL control).
- We focus on the degradation caused by torsion effects in the drive train.

i. Problem statement

ii. Proposed approach

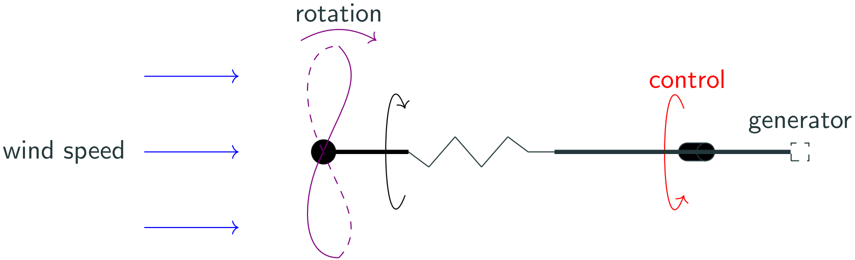
iii. Control design

iv. Results

v. Conclusion

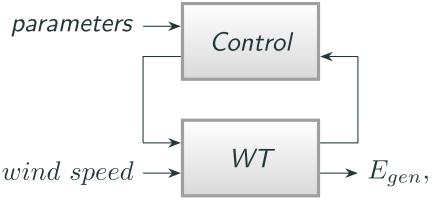
System behavior

Electrical energy is generated using the blades' movements caused by wind flowing trough.



- Thanks to a control system, rotation speed is controlled.

System behavior



- Such control is determined by given parameters to maximize energy generation.

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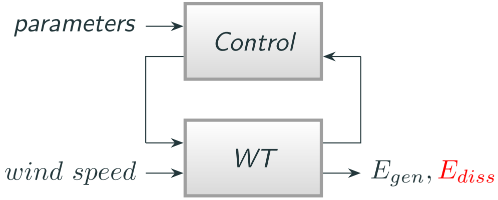

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- Torsions are inevitable in this process and they dissipate a certain amount of energy.

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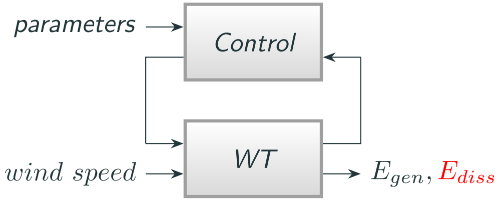
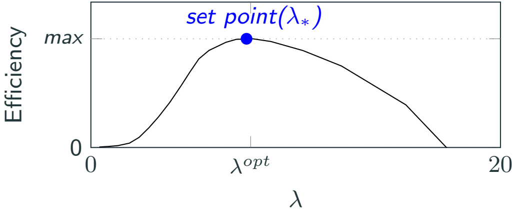


- Such control is determined by given parameters to maximize energy generation.
- Torsions are inevitable in this process and they dissipate a certain amount of energy.
- Let us assume that this energy loss is an image of the degradation observed during the lifetime of the system with a degradation-rate given by :

$$\dot{E}_{diss} = P_{diss} \tag{1}$$

System behavior

- Previous study[1] have shown that the degradation rate is affected by the control gain $k(\lambda_*)$ that depends on a parameter called λ_*.
  - $\rightarrow$ λ_* sets the operation point (usually) chosen to max energy output.



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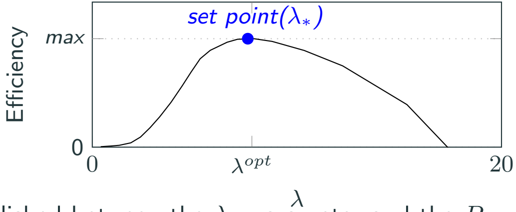

- If a relationship is established between the λ_* parameter and the P_{diss} values, the following function is obtained:

$$P_{diss} = \frac{B_{dt}\tilde{v}^2}{R^2}\lambda_*^2 + \eta \tag{2}$$

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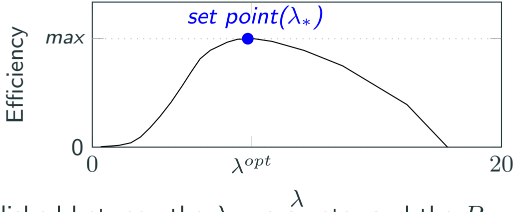

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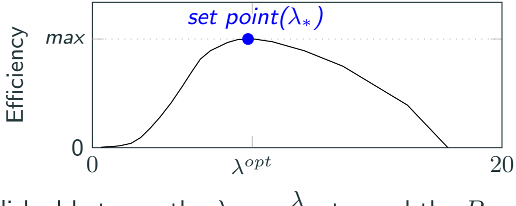

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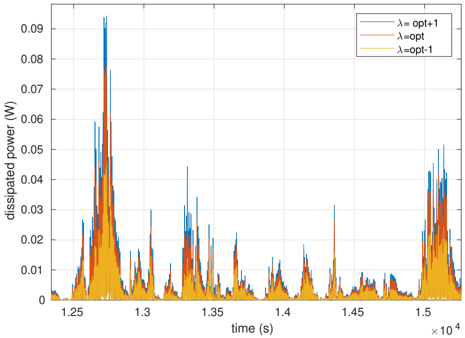
→ P_{diss} belongs to a set of values that depends on the set point λ_*, intensity of the turbulence of the wind $\tilde{v}$ and structural parameters (R and the stiffness coefficient B_{dt}).

System behavior; illustration



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Proposed strategy

- We propose to control the degradation rate by reconfiguring the control parameter λ_* with small variations.

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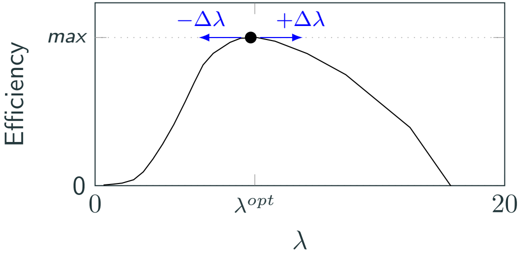

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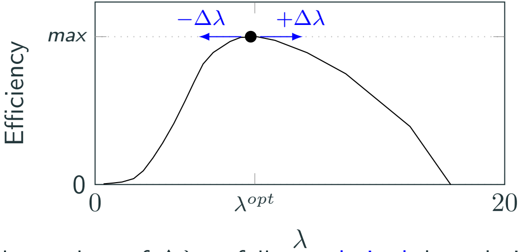

- A controller can calculate values of $\Delta\lambda$ to follow a desired degradation curve !

Proposed RUL control problem

- We propose to solve this problem by using a RUL control approach as follows:

RUL control problem

Find $\Delta\lambda$ that min. $\|\hat{P}_{diss} - P_{diss}^{ref}\|$ such that it enforces $E_{diss}(t = RUL^{ref}) = E_{diss}^{max}$.

- $\hat{P}_{diss}$: current degradation-rate, assumed to be estimated.
- P_{diss}^{ref} : desired degradation-rate calculated wrt desired remaining useful life RUL^{ref}.
- $E_{diss}(t = RUL^{ref})$: degradation level at desired RUL.

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- $E_{diss}(t = RUL^{ref})$: degradation level at desired RUL.
- RUL^{ref} must be adequately calculated to optimize the reliability/performance balance problem subject to operating limits.

RUL control solution: summary

- A state-space approach for RUL control has been already presented in (Felix et al. 2023)[2].
- Degradation curve is modeled as a linear or an exponential trend:

$$\dot{D} = \beta \text{ or } \dot{D} = \beta D \tag{4}$$

- We assume that the values of β can be affected by a manipulable process variable $\mathbf{w}$ through a **monotonic** relationship as follows:

$$\beta = \gamma f(\mathbf{w}) + \eta \tag{5}$$

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- Here, let's consider $D := E_{diss}$, $\beta := P_{diss}$ and $\mathbf{w} := \lambda_*$, so (5) becomes:

$$P_{diss} = \frac{B_{dt}\tilde{v}^2}{R^2}\lambda_*^2 + \eta \tag{6}$$

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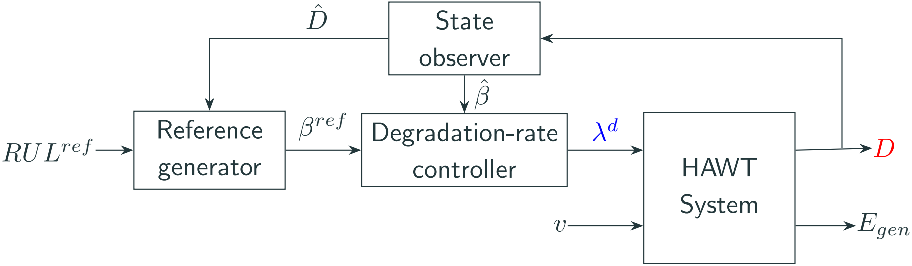
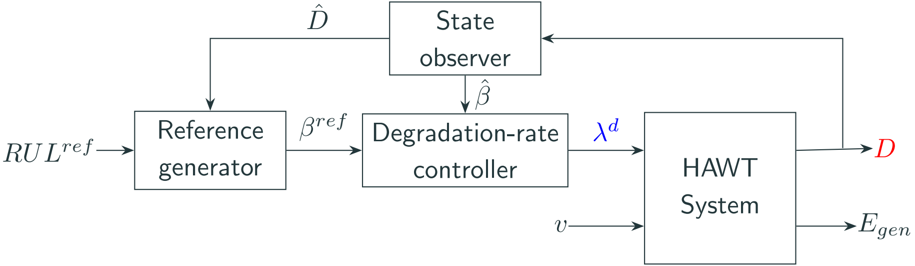
RUL control design: state-space approach



1. Find an appropriate $\beta^{ref}(RUL^{ref}, \hat{D})$ by using a **reference generator**.

RUL control design: state-space approach



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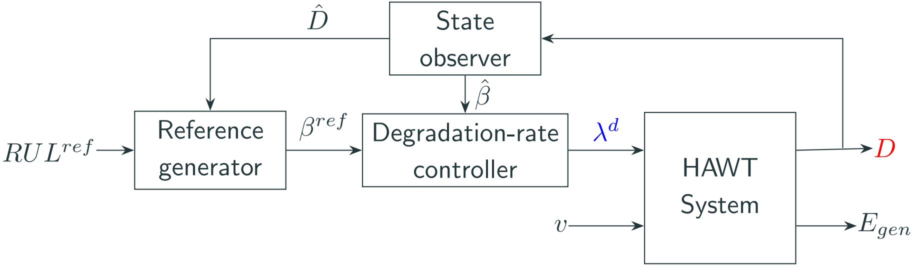

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3. Finally, find λ^d to $min\|\hat{\beta} - \beta^{ref}\|$ by using a **state-feedback controller**.

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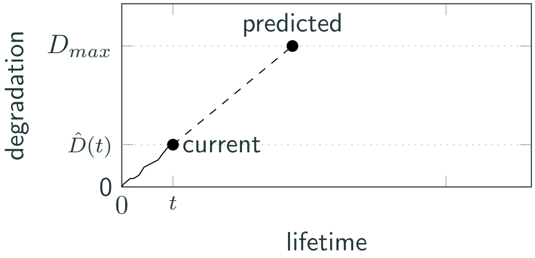
Reference generator

Objective: Find β^{ref} given RUL^{ref}.

If we consider a constant value β, degradation $D(t)$ reaches D_{max} as follows:

$$\hat{D}(t) + \beta \cdot RUL(t) = D_{max} \,, \qquad (7)$$

where $\hat{D}(t)$ is the current ("initial") state.



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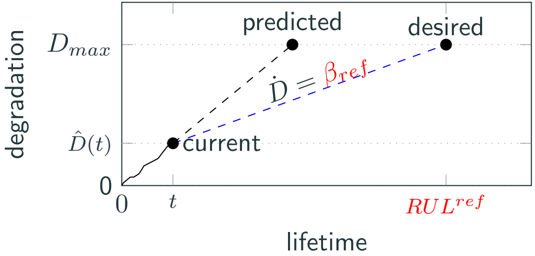

For a given $RUL(t) = RUL^{ref}$, there is a value β^{ref} that guarantees the following equality:

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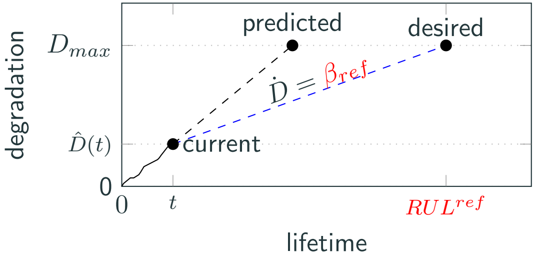

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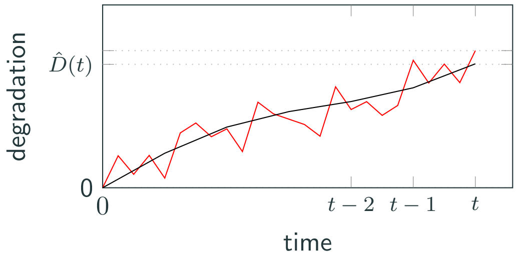
- β corresponds to a set of values of P_D bounded by operating conditions.

Observer design

Objective: Estimations of $[\hat{D}, \hat{\beta}]$.

- Focus on degradation **trend** observations:

$$\dot{D} = \beta \tag{9}$$



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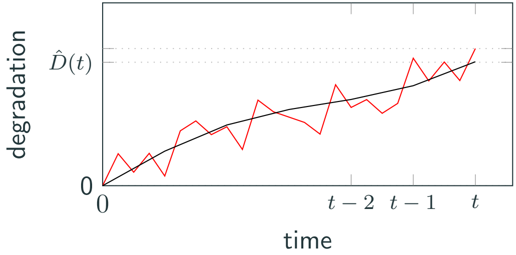

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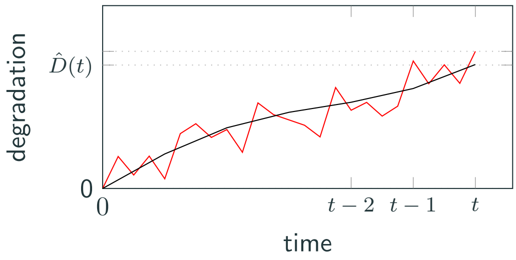
$$\dot{\hat{x}} = \begin{bmatrix} 0 & 1 \\ 0 & -c \end{bmatrix} \hat{x} + \mathbf{K}(y - \hat{y}) \tag{11}$$



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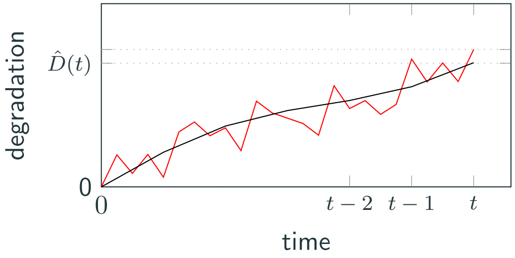

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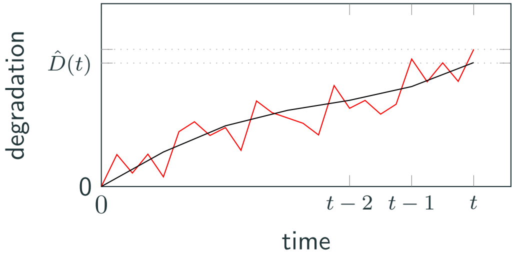

Here we consider observations of dissipated energy $y = E_D$.

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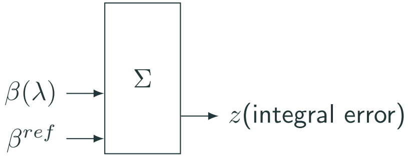
Control design (1)

Control objective: $min\|\hat{\beta} - \beta^{ref}\|$

The tracking error can be minimized by considering an **integral error** action:

$$z_{k+1} = z_k + \left(\beta_k - \beta_k^{ref}\right) . \quad (12)$$



If decisions have been taken in discrete-time, with possible **time-delay**, we model β_k following a dynamic given by:

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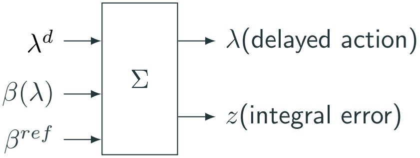

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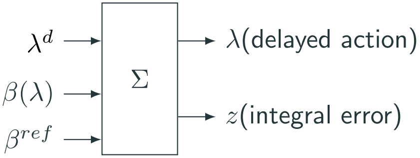

Σ : Integral error model for control design.

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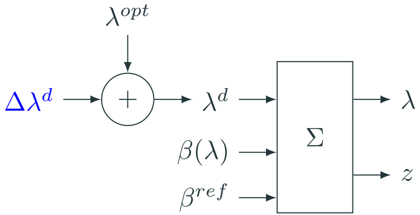
$$\lambda_k^d = \lambda^{opt} + \Delta\lambda_k^d ,$$



Thus, the system to control (in a linearized form), will be:

$$x_{k+1} = A(\gamma)x_k + Bu_k + Ed_k ,$$

with $x = [\Delta\lambda, z]$, $u = [\Delta\lambda^d]$, $d = [\Delta\beta^{ref}]$

function of the following parameter: $\gamma = 2\lambda^{opt}\frac{B_{dt}\tilde{v}^2}{R^2} \in [\gamma_{min}, \gamma_{max}]$

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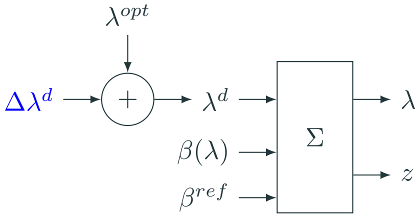

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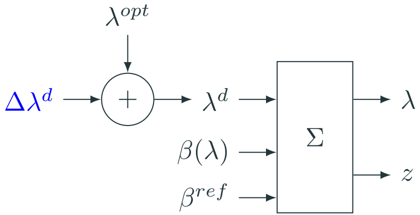
$$x_{k+1} = A(\gamma)x_k + Bu_k + Ed_k \,,$$

with $x = [\Delta\lambda, z]$, $u = [\Delta\lambda^d]$, $d = [\Delta\beta^{ref}]$

function of the following parameter: $\gamma = 2\lambda^{opt}\frac{B_{dt}\tilde{v}^2}{R^2} \in [\gamma_{min}, \gamma_{max}]$



Control design (2)

Here, we want to find λ_k^d around a nominal value λ^{opt}, i.e.

$$\lambda_k^d = \lambda^{opt} + \color{blue}{\Delta\lambda_k^d}\,,$$

Thus, the system to control (in a linearized form), will be:

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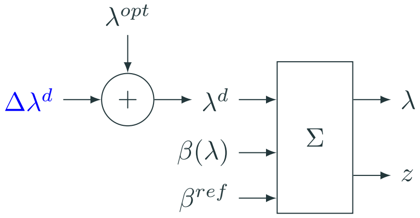


Remark: operating around λ^{opt} results

$$\beta = \beta(\lambda^{opt}) \pm \color{red}{\Delta\beta}$$

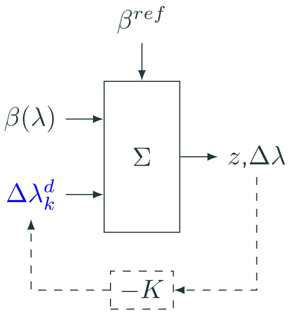
Control design (3)

Therefore, the control law will be implemented by using the following state-feedback:

$$\Delta\lambda_k^d = -K_1 \Delta\lambda_k - K_2 z_k \qquad (14)$$

We can find the gains K_1 and K_2 solution of a:

- LQR control problem, as proposed in (Felix et al. 2023b)[a], where γ is a constant



[a] Felix, Monica Spinola, John Martinez, and Christophe Bérenguer. "Remaining Useful Life Control of a Deteriorating Wind Turbine with Flexible-Shaft Drive-Train." ESREL 2023-33rd European Safety and Reliability Conference. Research Publishing Services, 2023.

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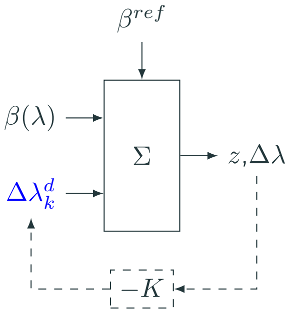
- LQR control problem, as proposed in (Felix et al. 2023b)[a], where γ is a constant
- Robust LQR problem, where γ is a bounded uncertain parameter where K stabilizes system for all γ values $A(\gamma_{min}) \leq A(\gamma) \leq A(\gamma_{max})$



i. Problem statement

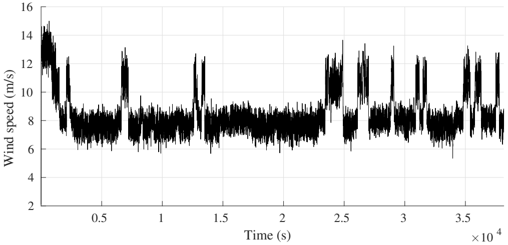
ii. Proposed approach

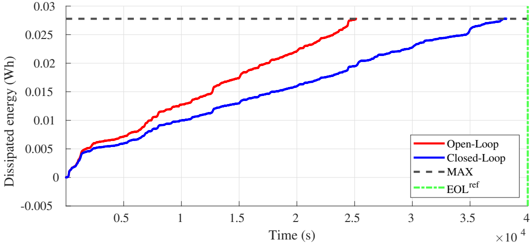
iii. Control design

iv. **Results**

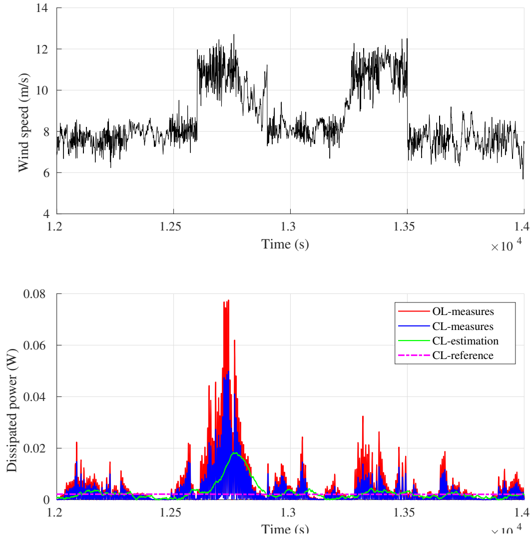
v. Conclusion

Results: Open loop vs. Closed loop

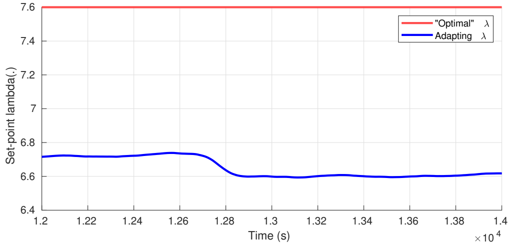


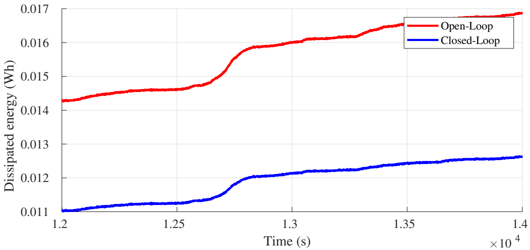


Results: Dissipated power (zoom in)



Results: Control response (zoom in)





Results: 10^3 realisations

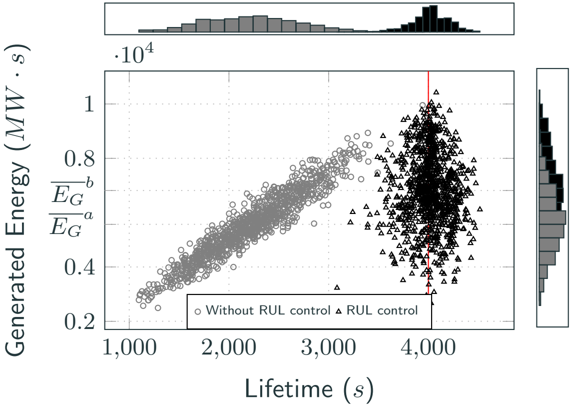
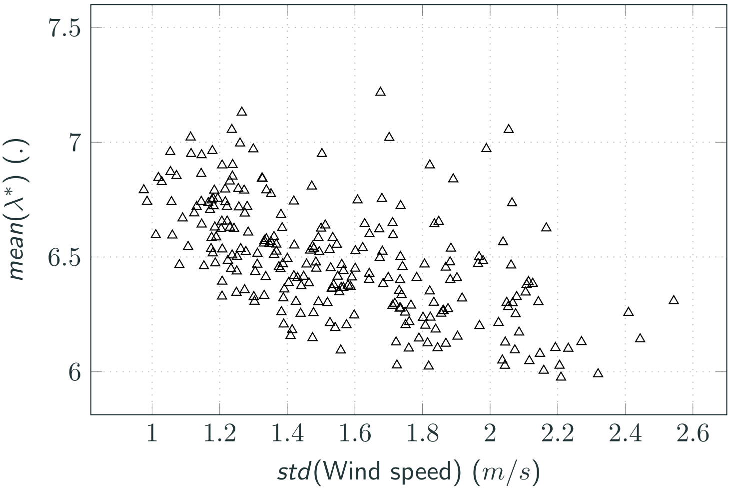


Figure 5: *Generated energy and lifetime for* 10^3 *simulated realizations with and without RUL control (*EoL^{ref} *equal to* $4000s$*).*

Results: Control response x wind speed variance



Conclusions and future perspectives

Main conclusions:

- Proposed approach extend the lifetime and still guarantee a nominal energy production.
- Adaptive control law can govern RUL by focusing on correction of the degradation-rate.
- A degradation model for control design can be obtained from the modeling of interactions of operating points of the system and dissipated energy.

Perspectives:

- Include other control systems into the RUL control problem (e.g, pitch control)
- Apply the proposed methodology to other applications.
- *To be discussed (?)*

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Thank you for your attention!!

Tracking problem: Control problem (Extra)

Wind speed is composed of:

$$v = \text{(mean) } \bar{v} + \text{(fluctuations) } \tilde{v}. \tag{15}$$

At the equilibrium point $\tilde{v} = 0$, the MPPT system guarantees:

$$\text{(blades side) } \omega_r^{eq} = \text{(generator side) } \omega_g^{eq} = \frac{\lambda^*}{R_r}\bar{v} \tag{16}$$

Then, because of a variation of the wind speed, the blades side is disturbed:

$$\omega_r \approx \frac{\lambda^*}{R_r} v \tag{17}$$

It results a relative speed:

$$\tilde{\omega} = \omega_r - \omega_g^{eq}. \tag{18}$$

that causes torsion and dissipates energy:

$$P_D = B_{dt}\tilde{\omega}^2 \tag{19}$$

Therefore, we have the final relationship:

$$P_D \approx \frac{B_{dt}\tilde{v}^2}{R_r^2}{\lambda^*}^2 \tag{20}$$

References