Sensorless frequency-converter-based methods for LCC efficient pump and fan systems

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Outline of the presentation

I. Role of a frequency converter in pump and fan systems

II. Sensorless estimation of the system operational state

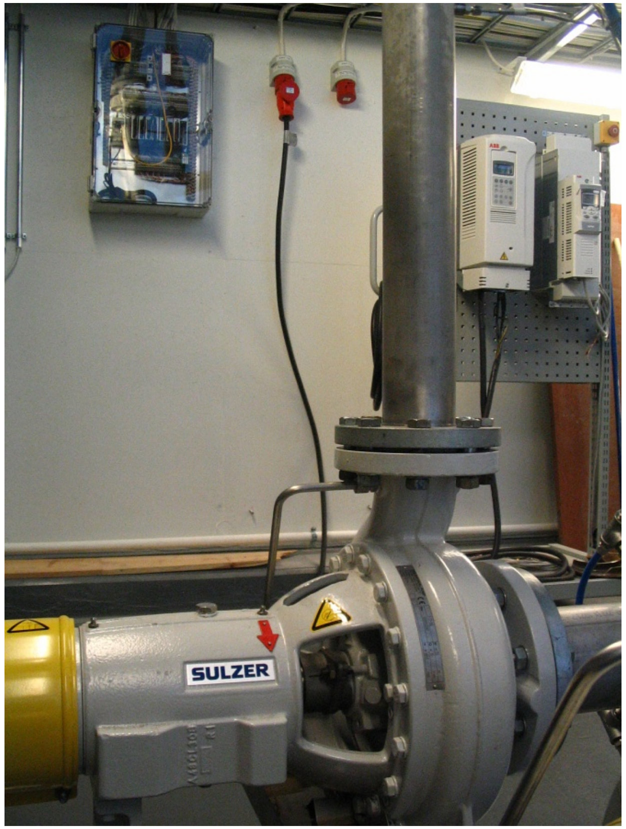
III. Identification of system characteristics

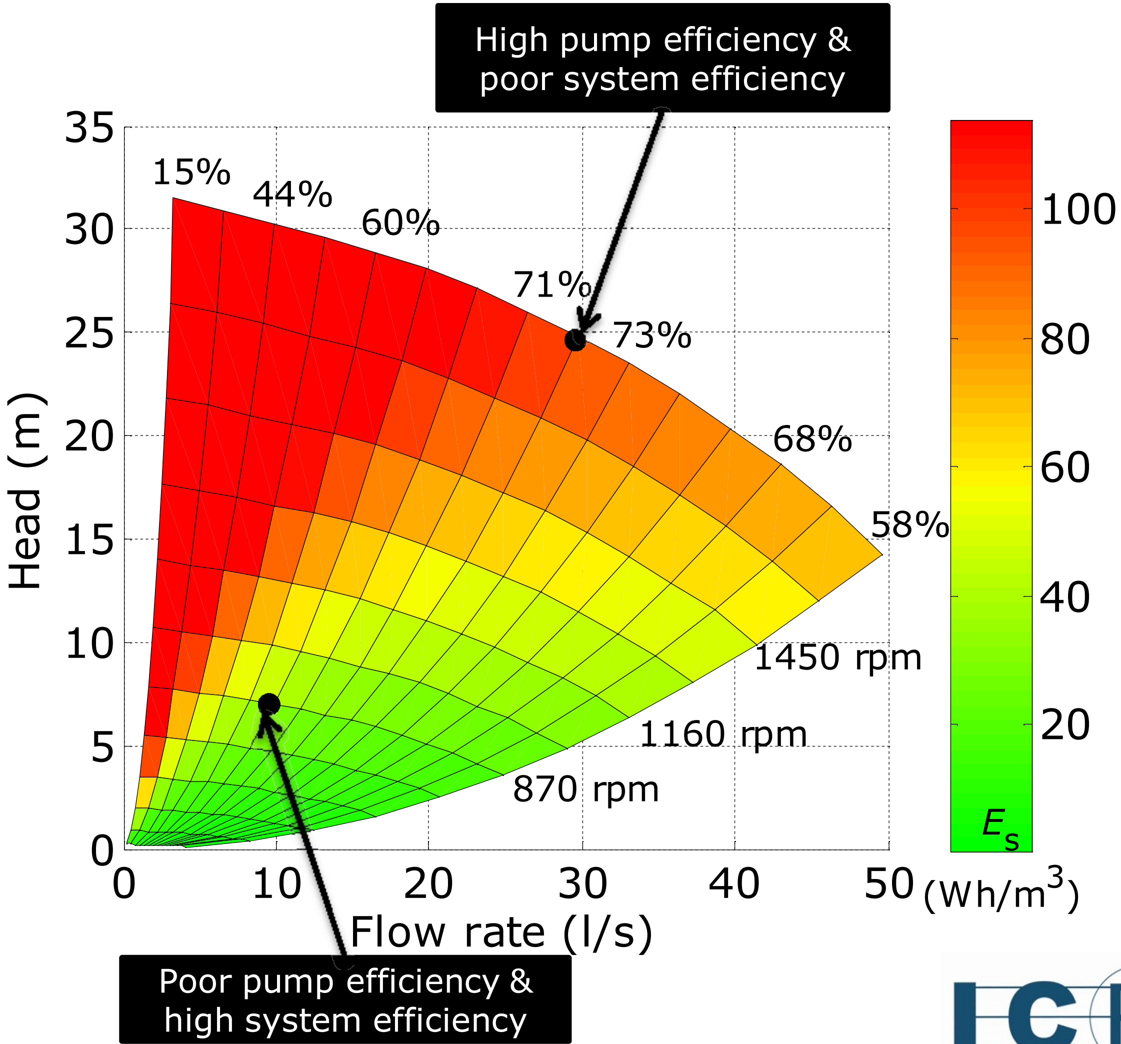
IV. Energy efficient system control with variable-speed usage

V. Identification of operational states that reduce the system lifetime or cause an immediate failure

Part I: Role of a frequency converter in pump and fan systems

Frequency converter allows variable-speed system operation





Frequency converter as a sensorless measurement unit

- Converters with internal current and voltage measurements can provide estimates for
  - Rotational speed, shaft torque and power
  - Motor current and temperature
  - System energy consumption
  - System run-time
- These can be used to determine
  - System operational state (flow rate, head, efficiency)
  - System energy efficiency E_s (kWh/m^3)
  - Distribution of flow rate, E_s etc.

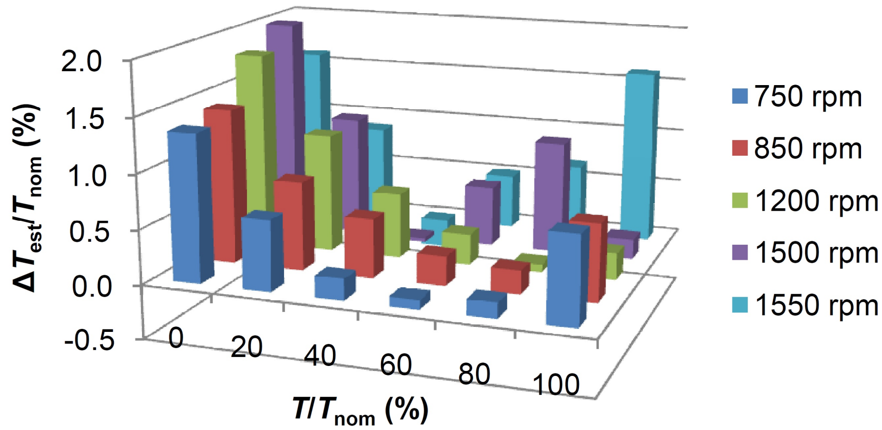
Parameters
- 01: ACTUAL SIGNALS
- 02: ACTUAL SIGNALS
- 03: INTERNAL DATA
- 05: PFC WORDS
- 09: ACTUAL SIGNALS
- 10: START/STOP/DIR
- 11: REFERENCE SELECT
- 12: CONSTANT FREQ
- 13: ANALOGUE INPUTS
- 14: RELAY OUTPUTS
- 15: ANALOGUE OUTPUTS
- 16: SYSTEM CTR INPUTS
- 20: LIMITS

Name	Value
01.02: MOTOR SPEED FILT [rpm]	900.0
01.04: MOTOR CURRENT [A]	9.4
01.05: MOTOR TORQ FILT2 [%]	21.2
01.06: POWER [%]	12.8
01.15: KILOWATT HOURS [kWh]	555.5
01.37: MOTOR TEMP EST [C]	30.0
01.43: MOTOR RUN-TIME [h]	114.8
05.11: ACT FLOW [m3/h]	38.8
05.12: SUM FLOW [m3]	2790.1

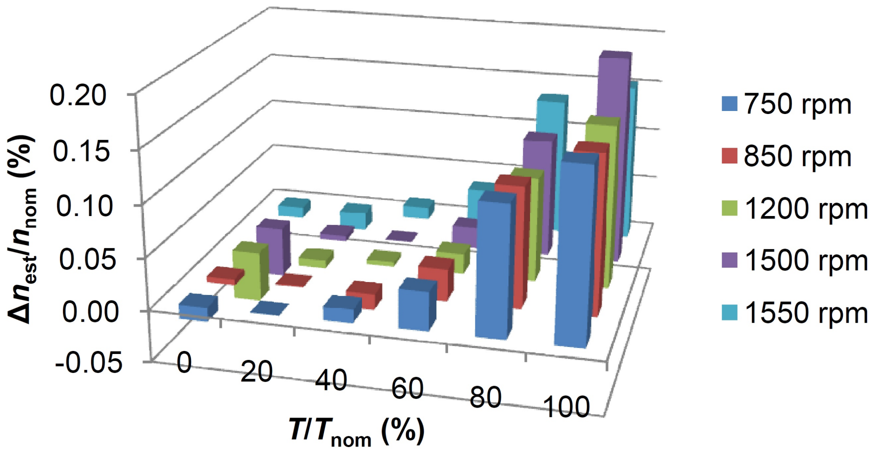
Estimation accuracy of a DTC frequency converter

37 kW, 1480 rpm induction motor

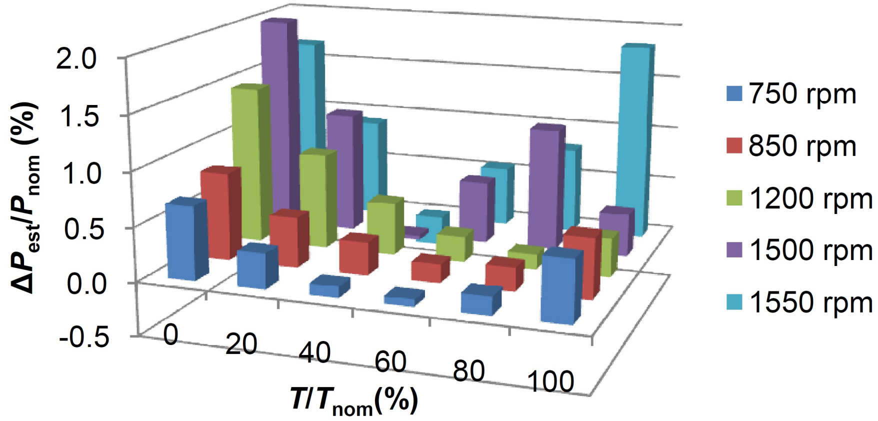
Torque estimation errors within 4.9 Nm (2.1 %)



Speed estimation errors within 3.1 rpm (0.2 %)



Power estimation errors within 0.77 kW (2.1 %)



Ref.: T. Ahonen et al., “Accuracy study of frequency converter estimates used in the sensorless diagnostics of induction-motor-driven systems,” in *Proc. EPE 2011 Conf.*, pp. 1–10.

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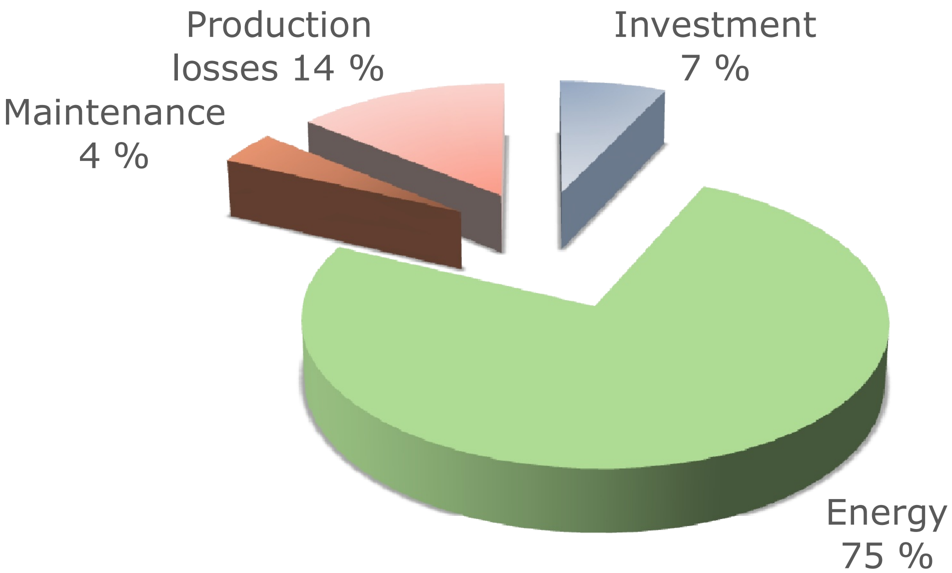
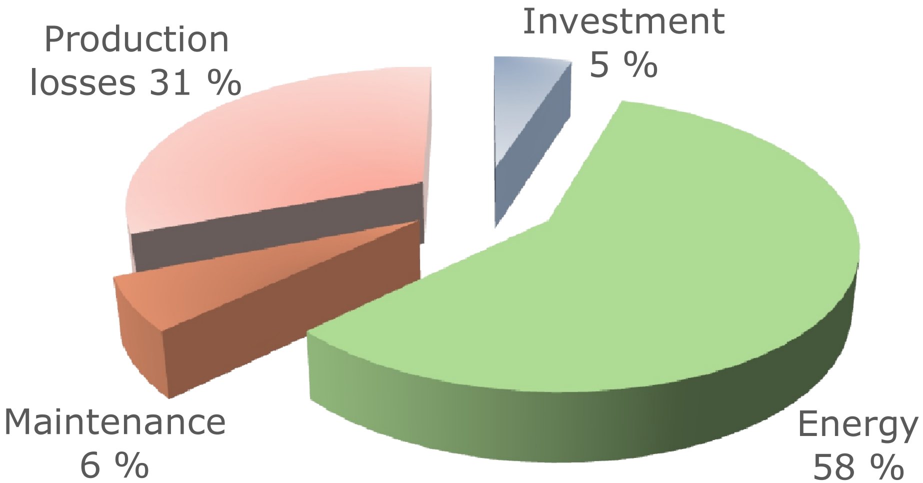
Life-cycle costs in pump and fan systems dominated by energy, bounded by design





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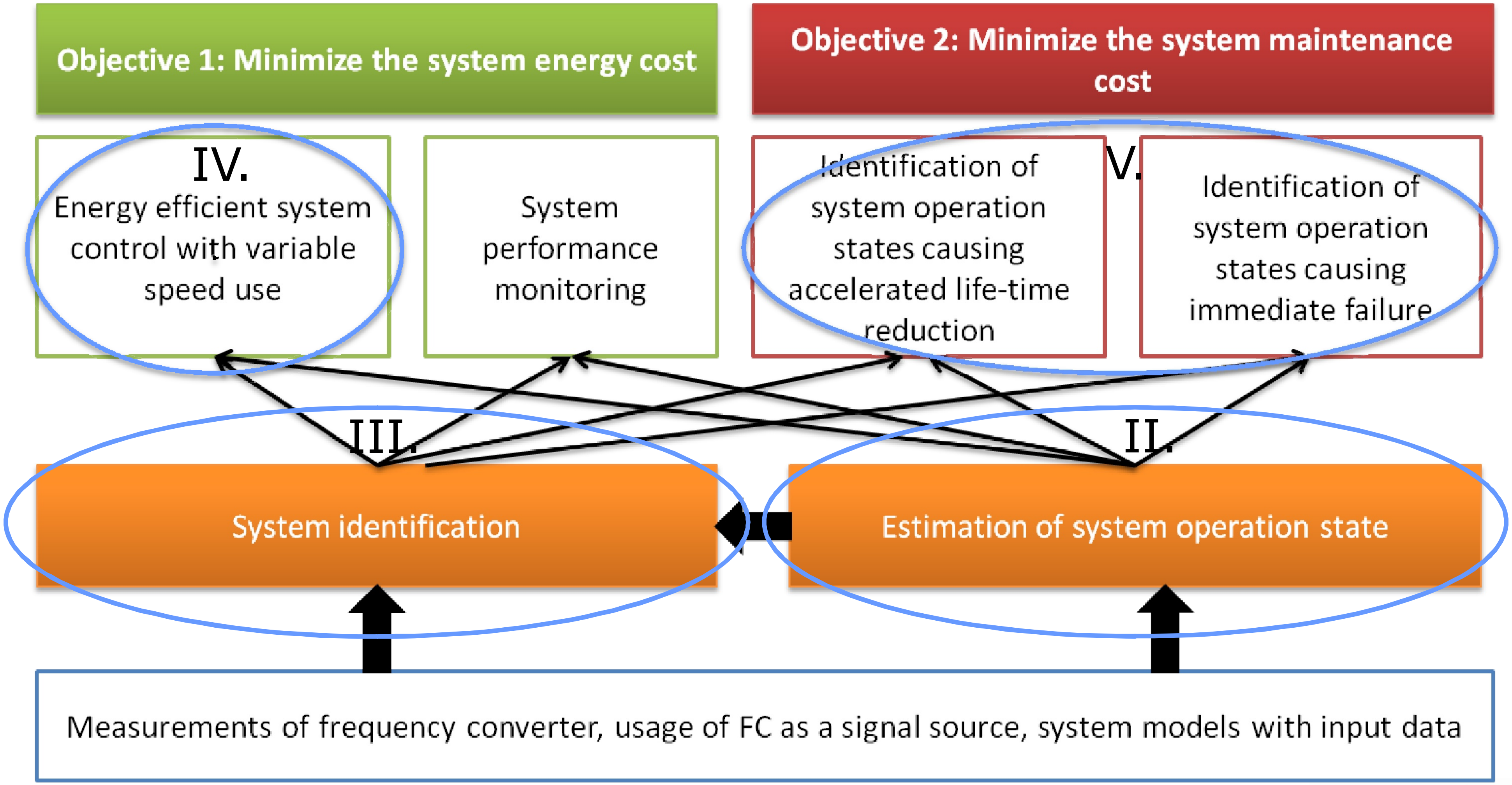
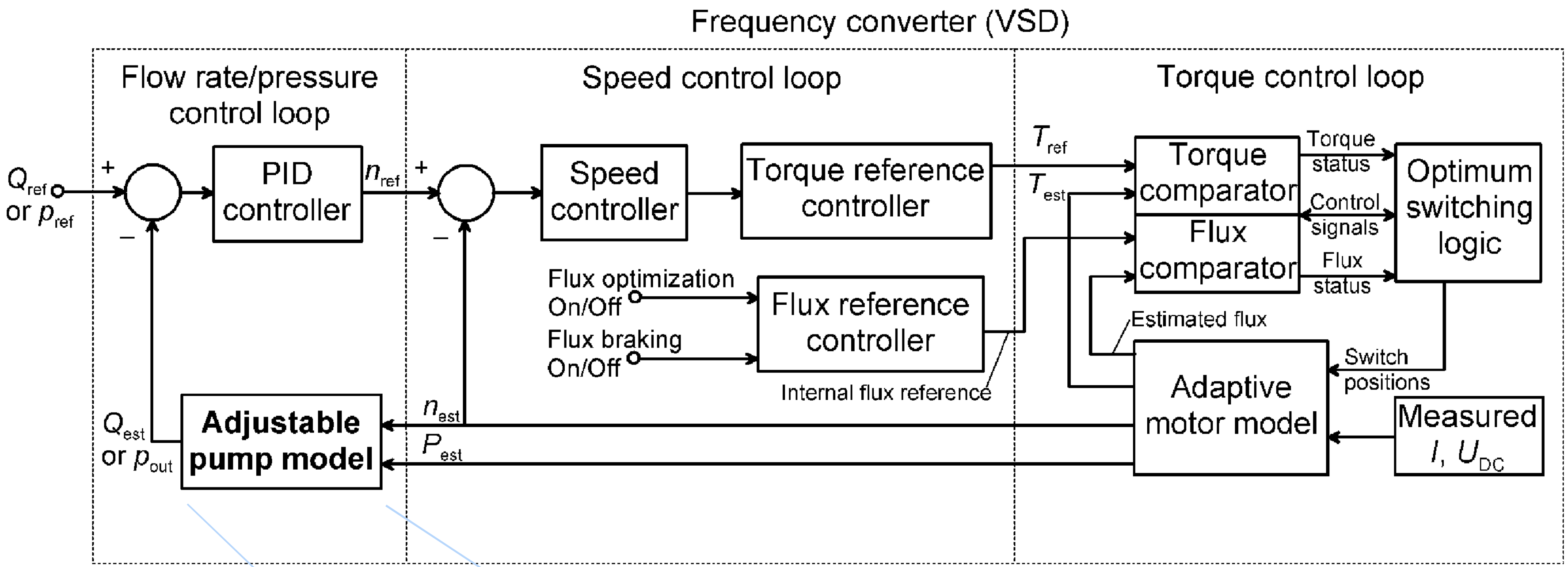
Role of a frequency converter in LCC efficient pump and fan systems

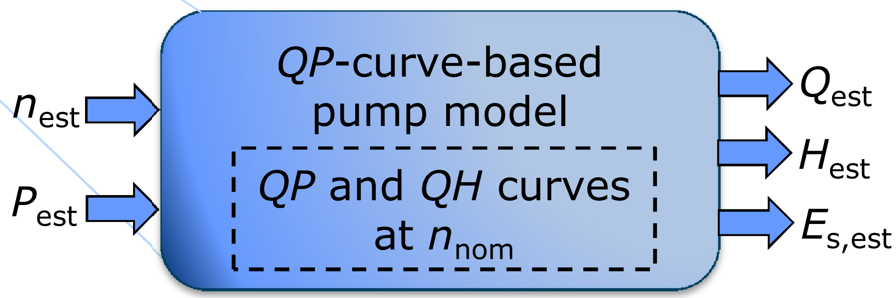


Part II: Sensorless estimation of the system operational state

Sensorless system state estimation by a frequency converter

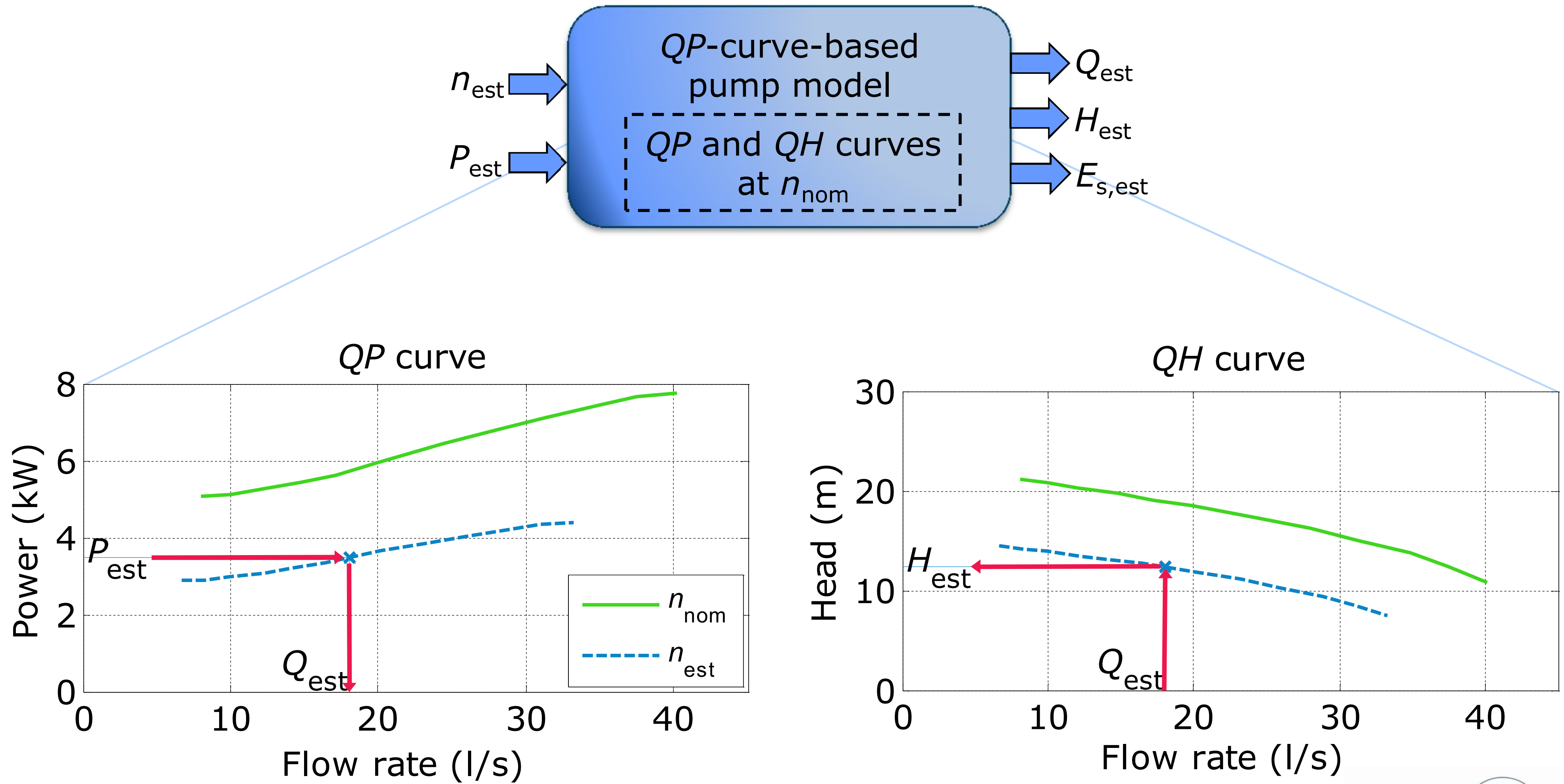


A parameter-adjustable pump or fan model can be implemented into the converter control scheme.



The model provides estimates for the system operational state and energy efficiency that can be further used for process identification and energy efficiency optimization.

QP-curve-based pump model



Ref.: T. Ahonen et al., “Estimation of pump operational state with model-based methods,” *Energy Conversion and Management,* vol. 51, no. 6, pp. 1319–1325, June 2010.

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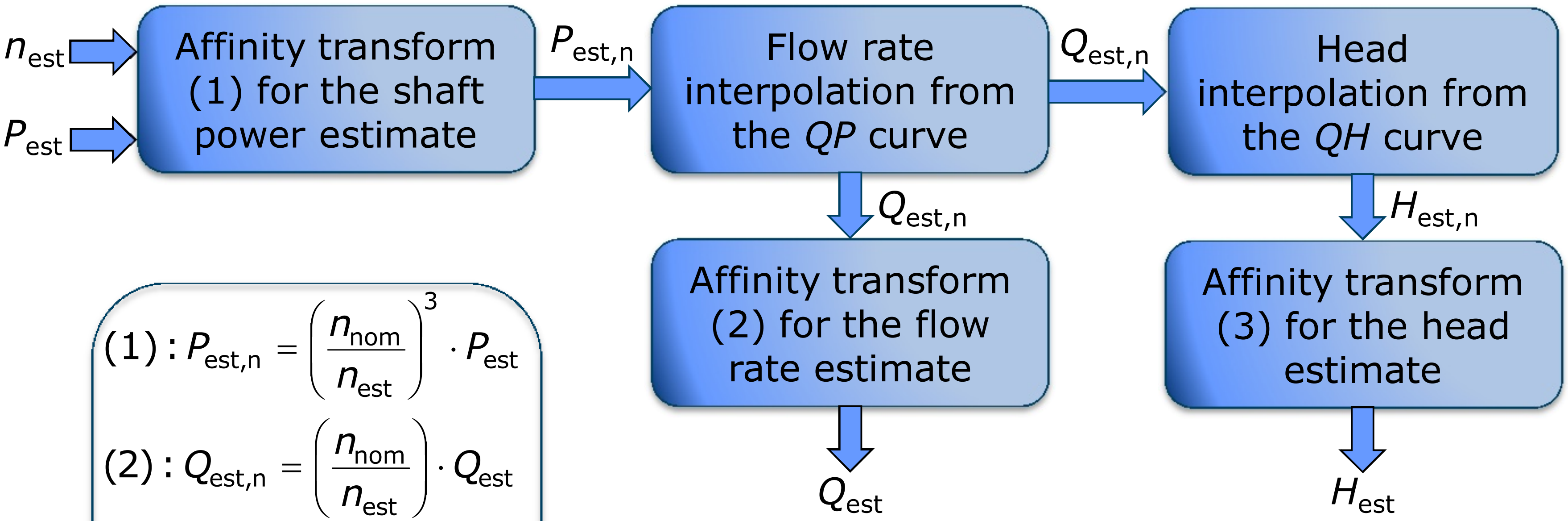
Operation of a *QP*-curve-based pump model

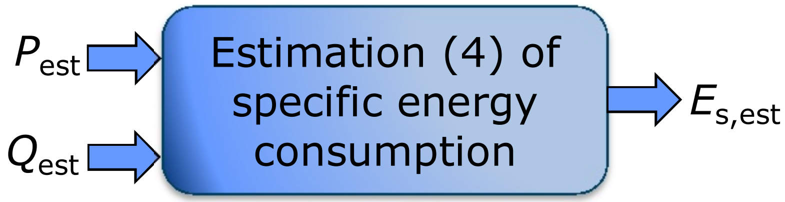


$$(1): P_{\mathrm{est,n}} = \left(\frac{n_{\mathrm{nom}}}{n_{\mathrm{est}}}\right)^3 \cdot P_{\mathrm{est}}$$

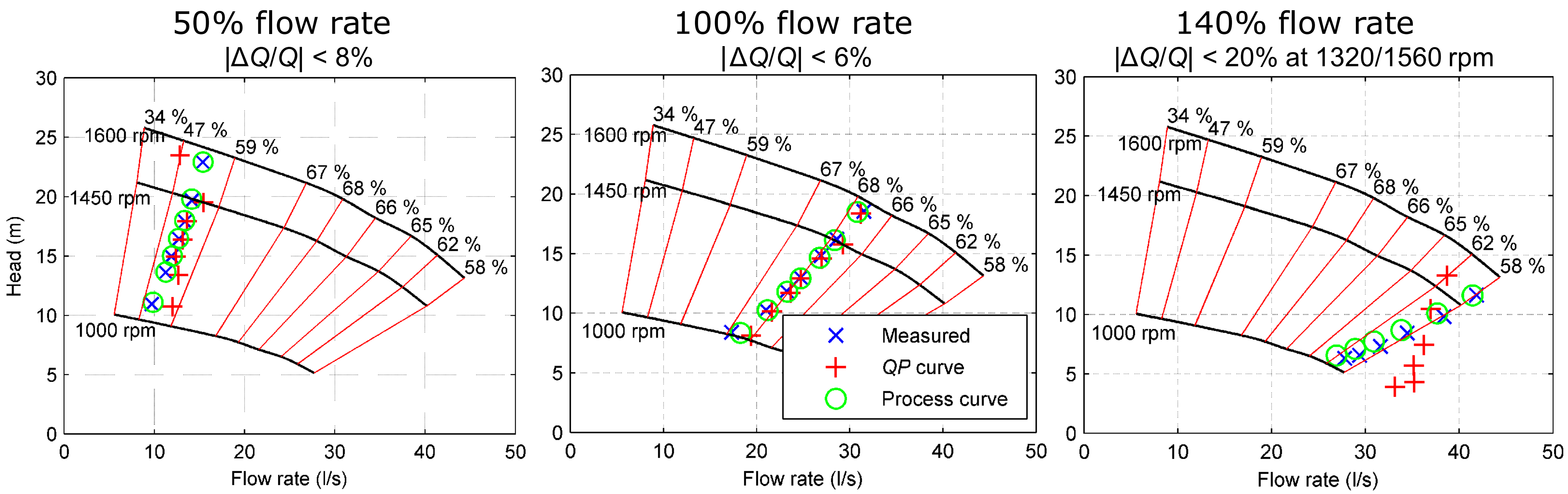
$$(2): Q_{\mathrm{est,n}} = \left(\frac{n_{\mathrm{nom}}}{n_{\mathrm{est}}}\right) \cdot Q_{\mathrm{est}}$$

$$(3): H_{\mathrm{est,n}} = \left(\frac{n_{\mathrm{nom}}}{n_{\mathrm{est}}}\right)^2 \cdot H_{\mathrm{est}}$$

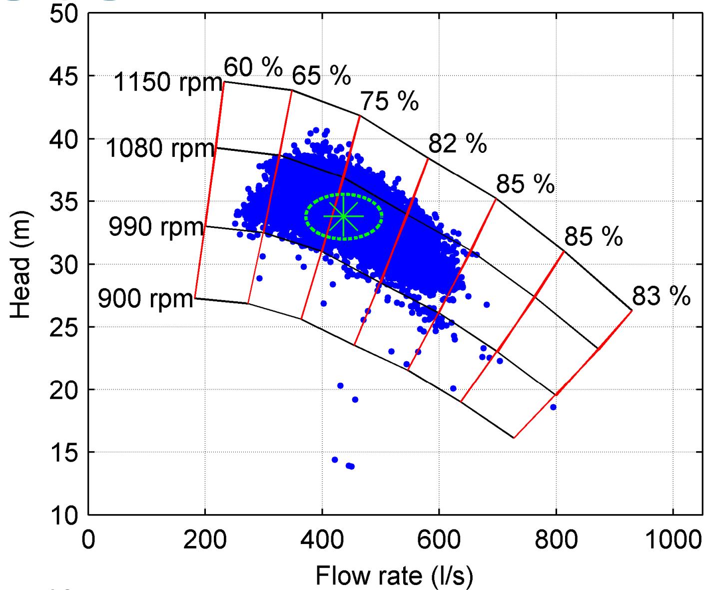
$$(4): E_{\mathrm{s,est}} = \frac{P_{\mathrm{est}}}{Q_{\mathrm{est}}}$$



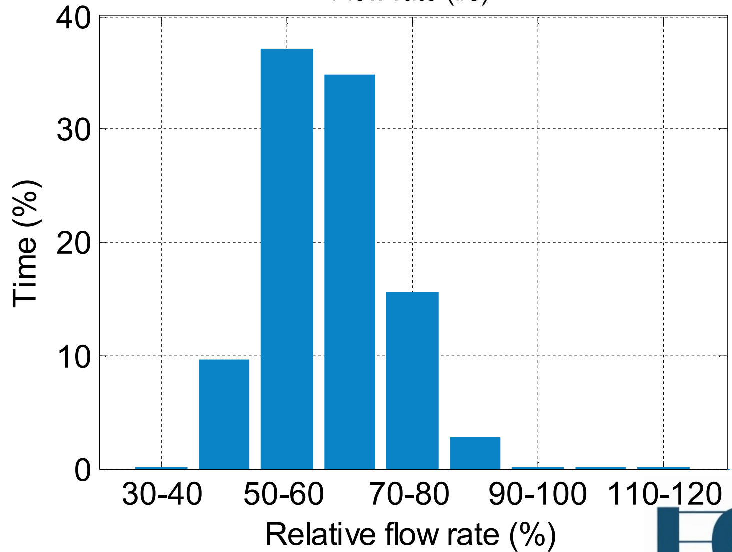
Estimation accuracy of the *QP*-curve-based pump model



Pilot test results for an industrial pulp pump system



- Sulzer ARP54-400 centrifugal pump
- Typical pump eff. 76%, max. eff. 85%
- Typical pump power cons. 240 kW
- 9% efficiency improvement equals 25kW lower power consumption



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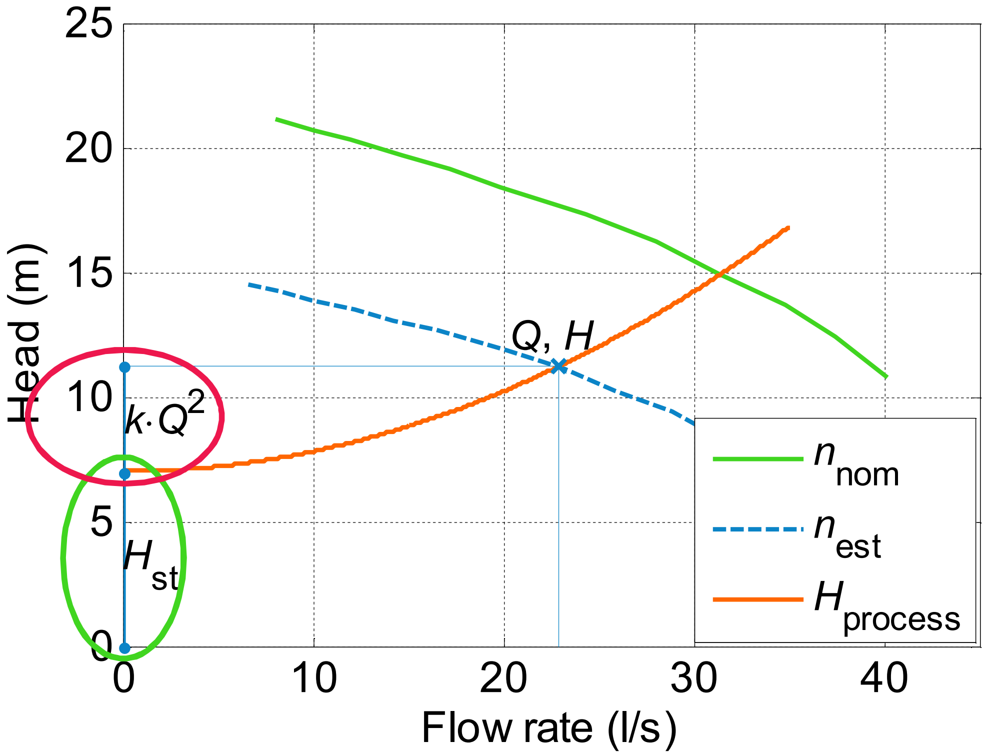
Part III: Identification of system characteristics

Surrounding system characteristics

- Pump/fan operating point lies in the intersection of the device and surrounding process characteristic curves



$$H = \boxed{H_{st}} + \boxed{k \cdot Q^2}$$

$$E_s = \frac{P_{tot}}{Q} = \frac{\rho \cdot g \cdot \boxed{H}}{\eta_{dt} \cdot \eta_p}$$

Minimum level of energy usage:

$$E_{s,min} = \rho \cdot g \cdot H_{st}$$

Ref.: T. Ahonen et al., "Generic unit process functions set for pumping systems," in *Proc. EEMODS 2011 Conf.*

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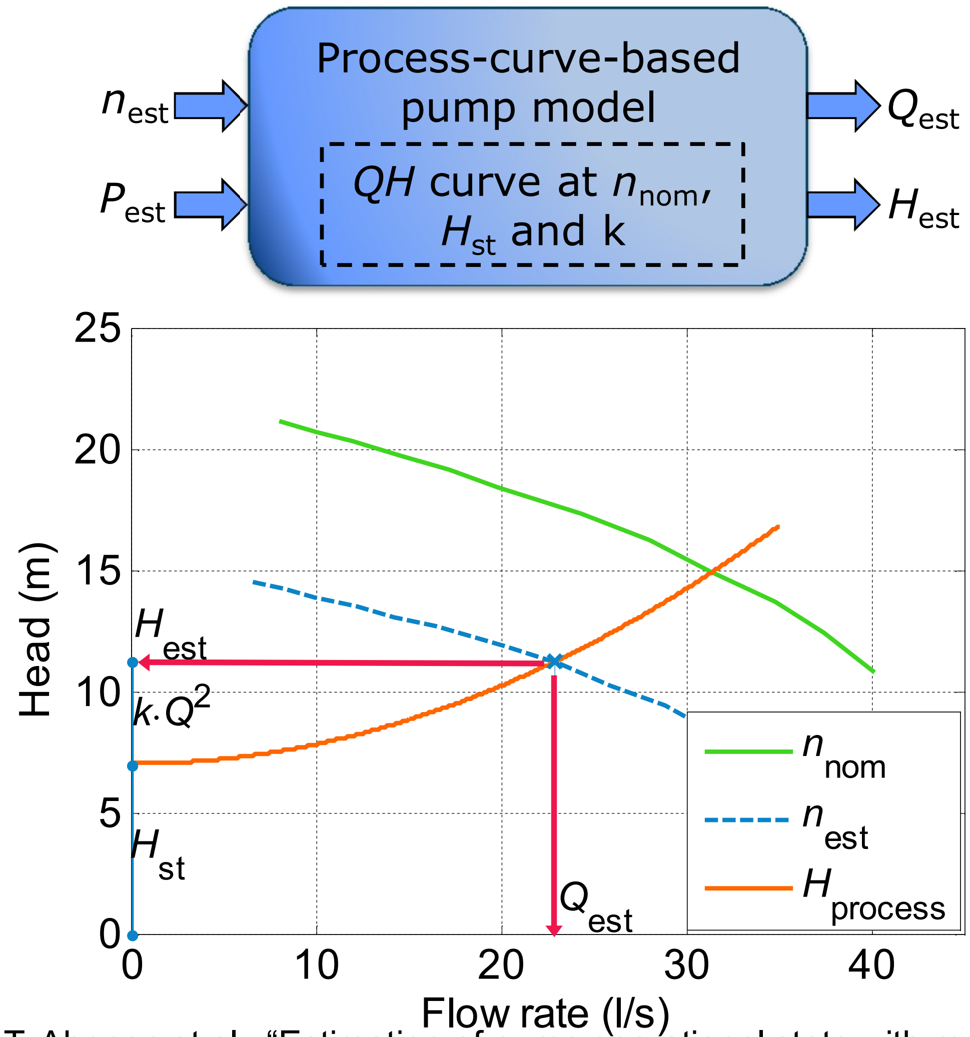
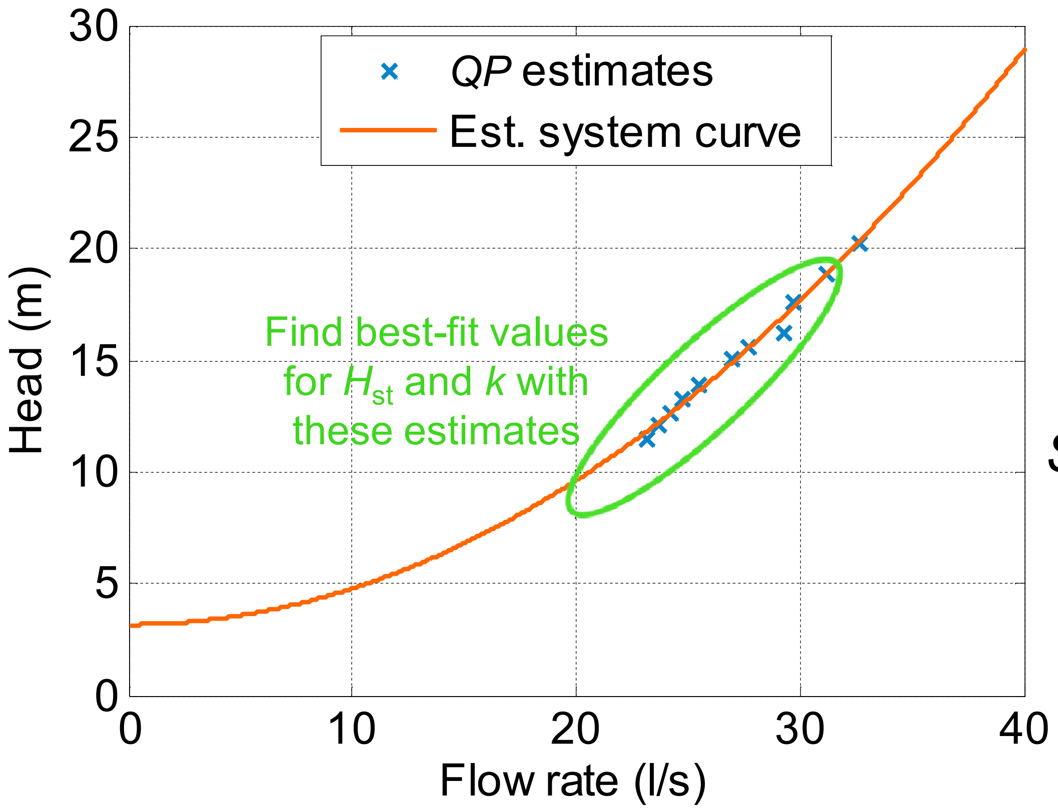
State estimation with the process-curve-based pump model



Ref.: T. Ahonen et al., "Estimation of pump operational state with model-based methods," *Energy Conversion and Management,* vol. 51, no. 6, pp. 1319–1325, June 2010.

Identification of the surrounding system

– H_{st} and k can be determined with applicable QP curve model estimates (Q_{est}, H_{est}) using the LMS method



$$H_{process} = H_{st} + k \cdot Q^2$$

$$S = \sum_{i=1}^{m} \left(H_{est,i} - H_{st} - k \cdot Q_{est,i}^2 \right)^2$$

Ref.: T. Ahonen et al., "Frequency-converter-based hybrid estimation method for the centrifugal pump operational state," *IEEE Trans. Ind. Electron.*, vol. 59, no. 12, pp. 4803–4809, December 2012.

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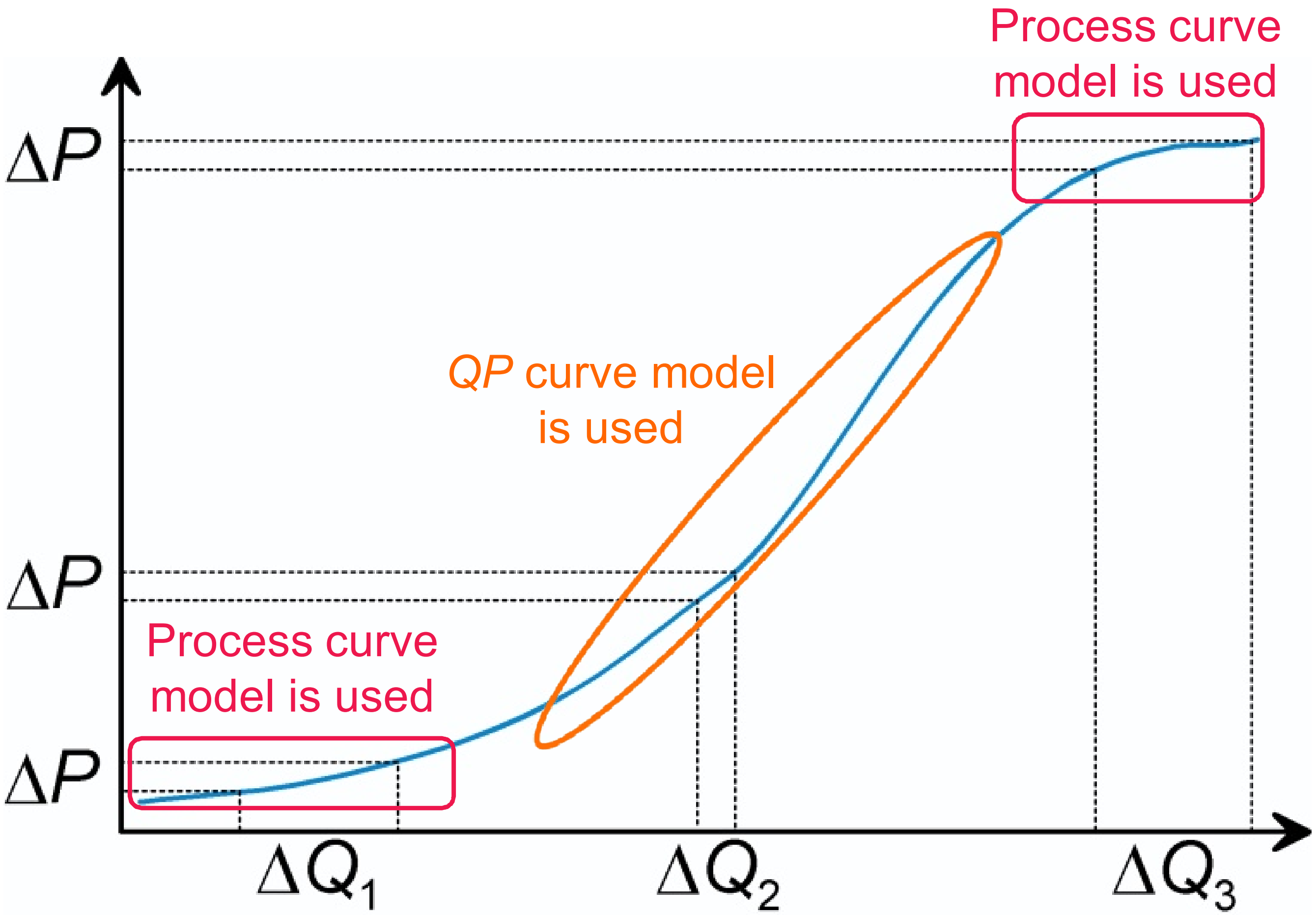
Combined (hybrid) usage of the pump models

– Process-curve-based model is used when operating on the flat part of the *QP* curve



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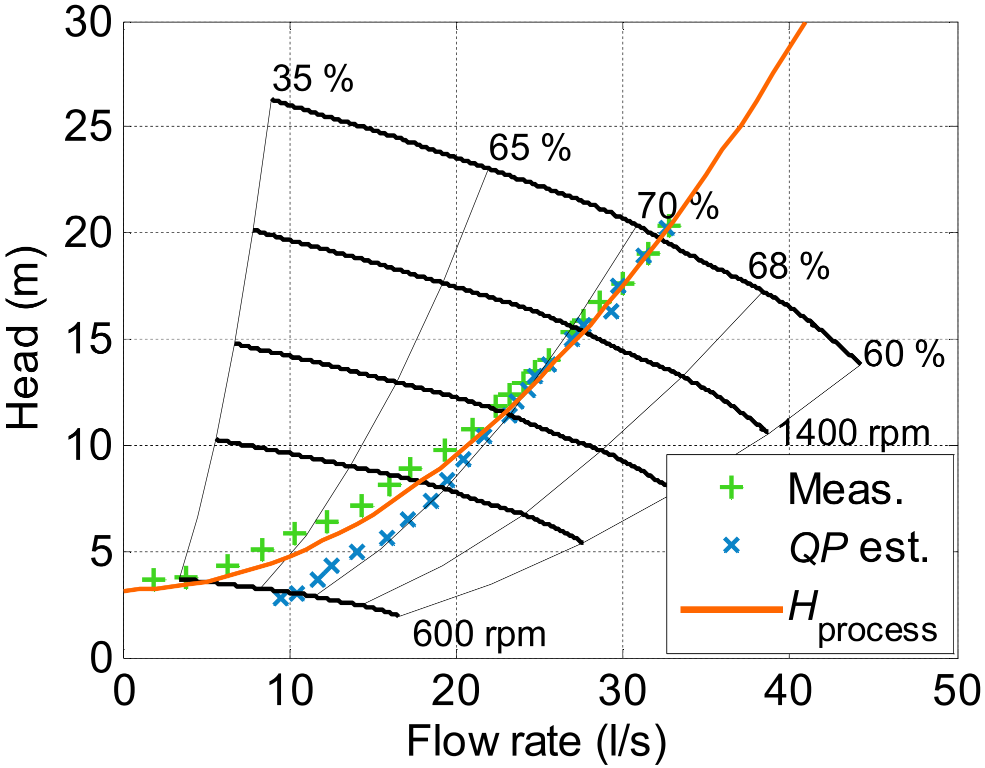
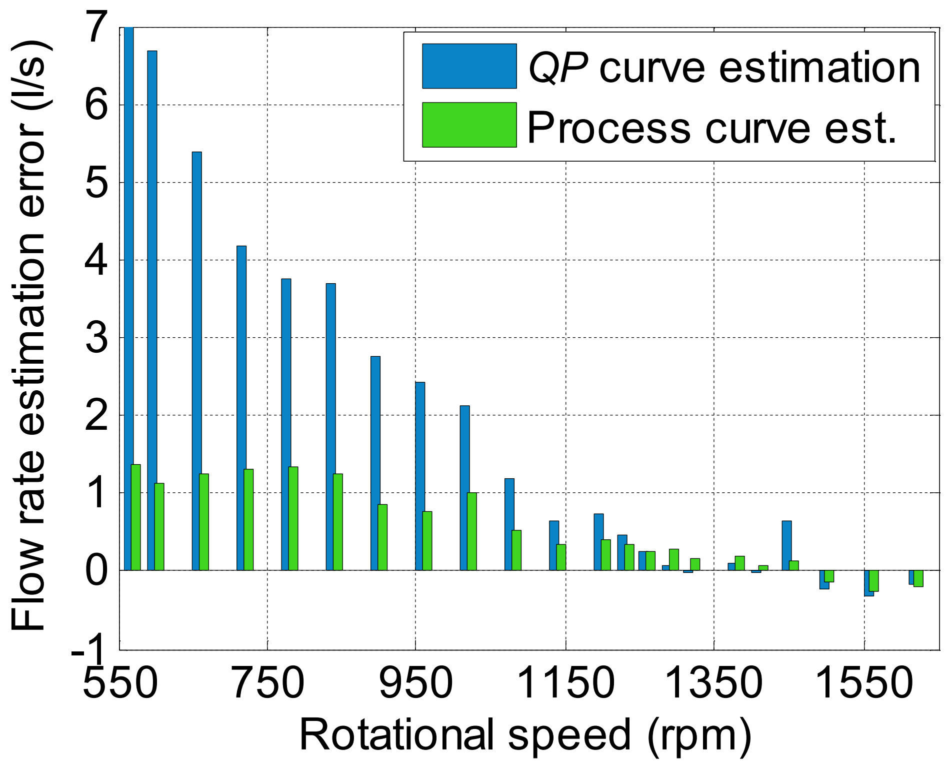
Estimation accuracy of the process-curve-based pump model

– Process curve parameters were determined with 11 *QP* curve model estimates at 1160–1620 rpm





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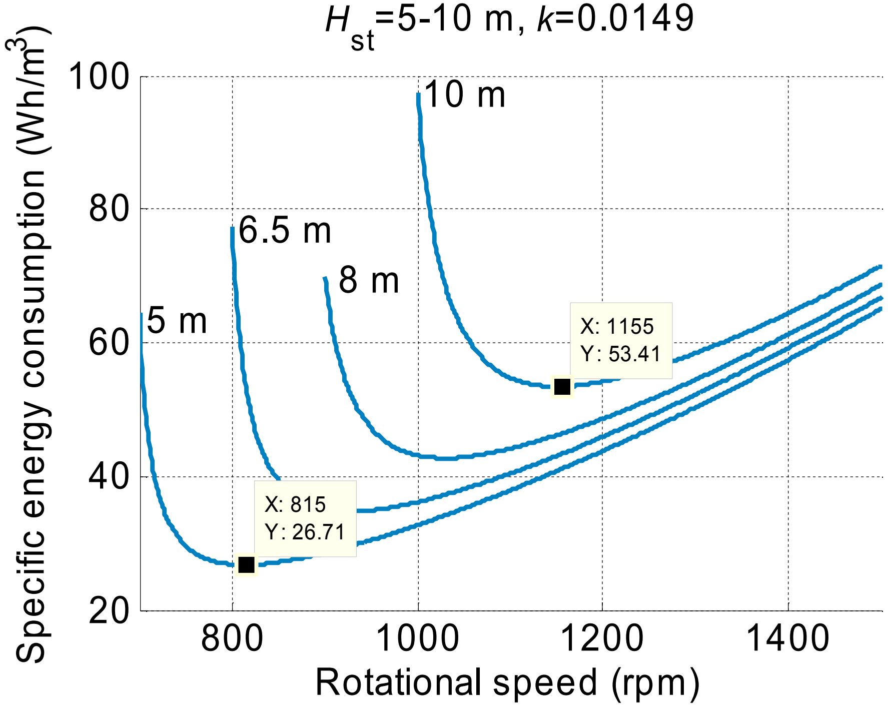
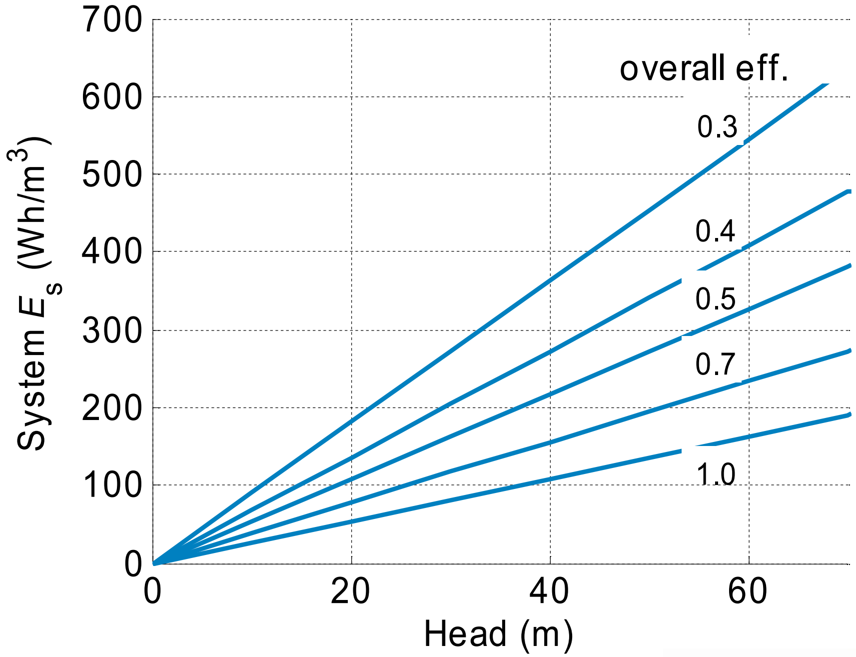
Part IV: Energy efficient system control with variable-speed usage

How to achieve the minimum energy consumption?

1. Drive the system as <u>energy efficiently</u> as possible
2. Minimize the hydraulic losses (H_{st}, k)
3. Use high efficiency components in the system





Ref.: T. Ahonen et al., “Generic unit process functions set for pumping systems,” in *Proc. EEMODS 2011 Conf.*

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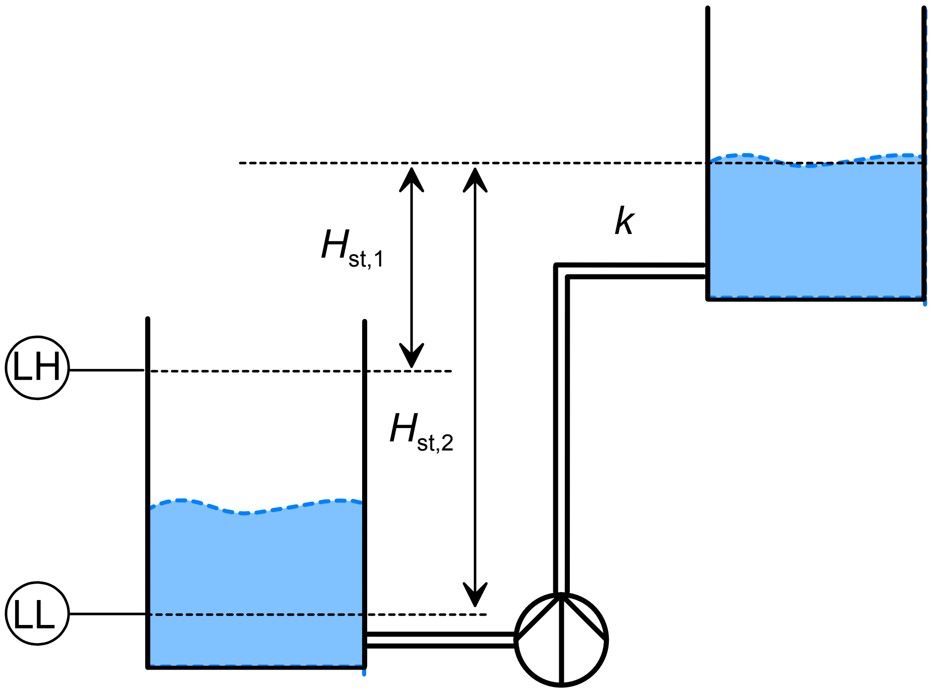
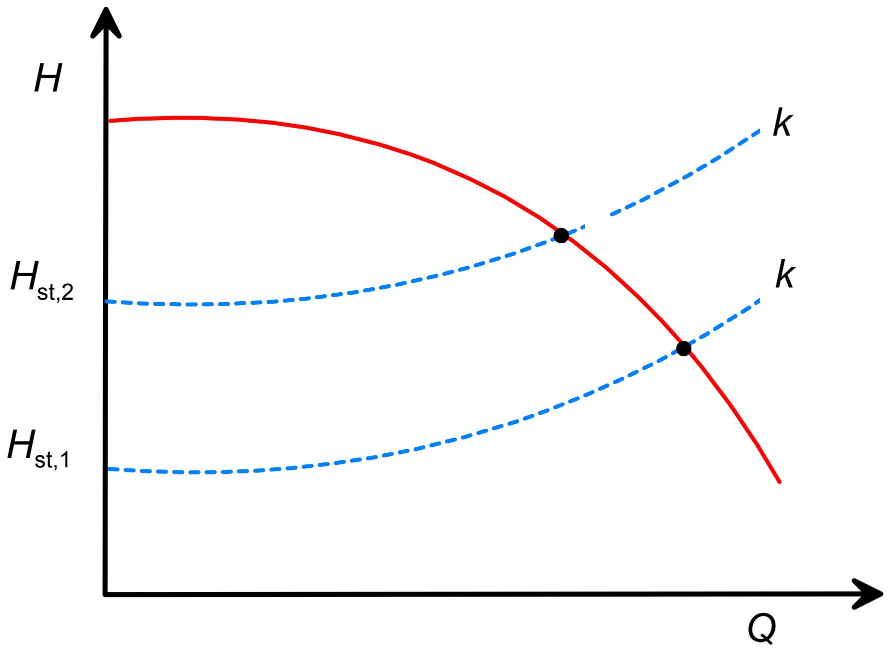
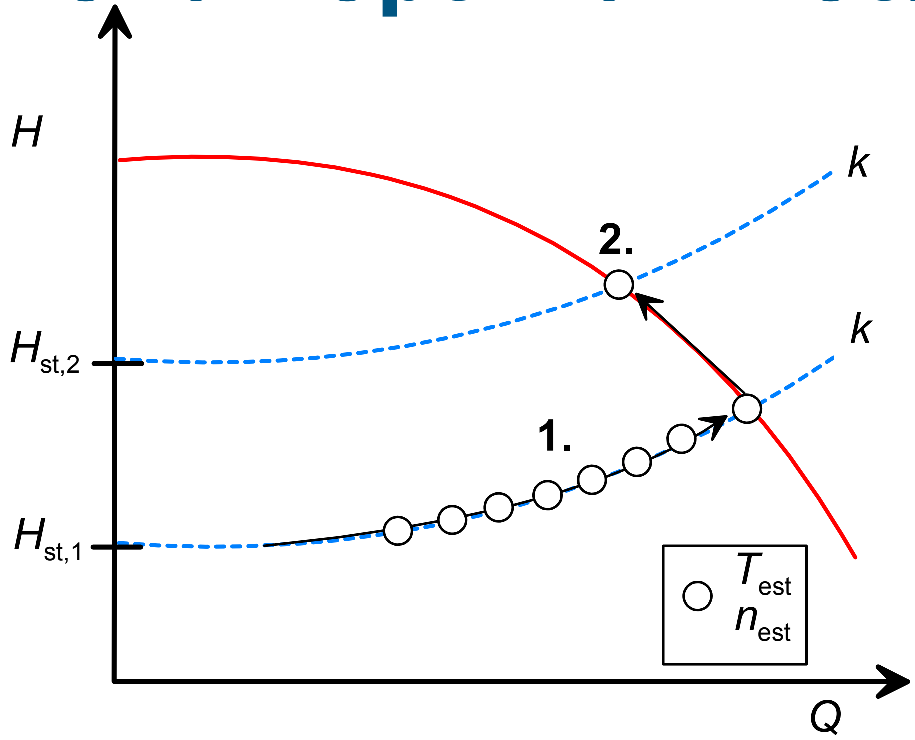
Energy efficient filling of a reservoir with a variable-speed pumping system

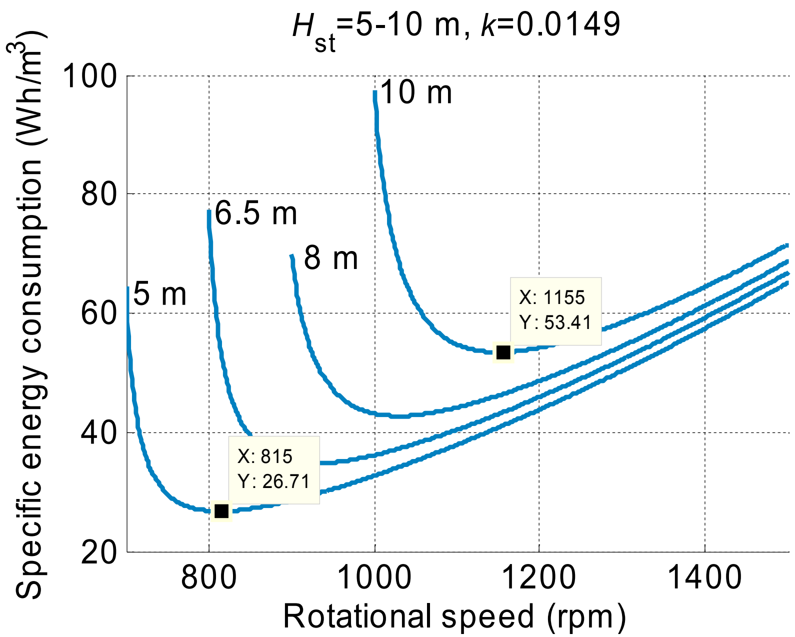
- Variable-speed operation allows energy efficient filling of a reservoir, but at which rotational speeds?

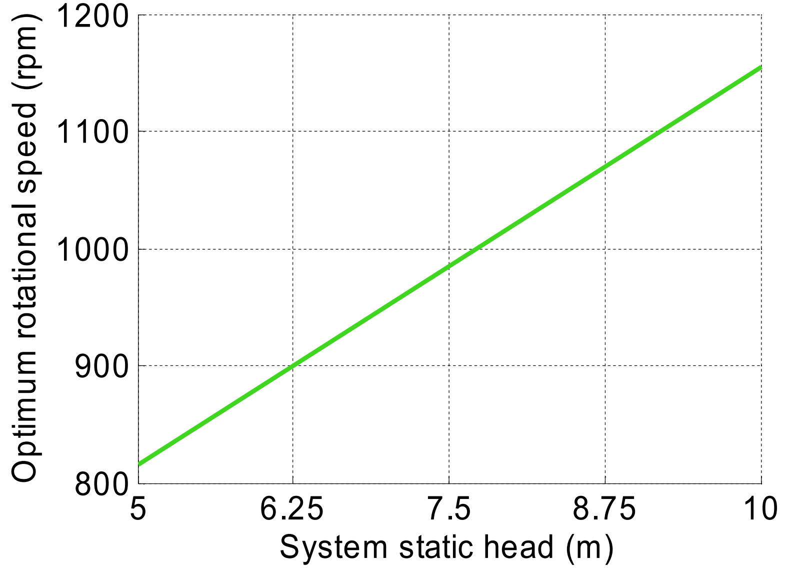




System identification and determination of an optimum rotational speed profile

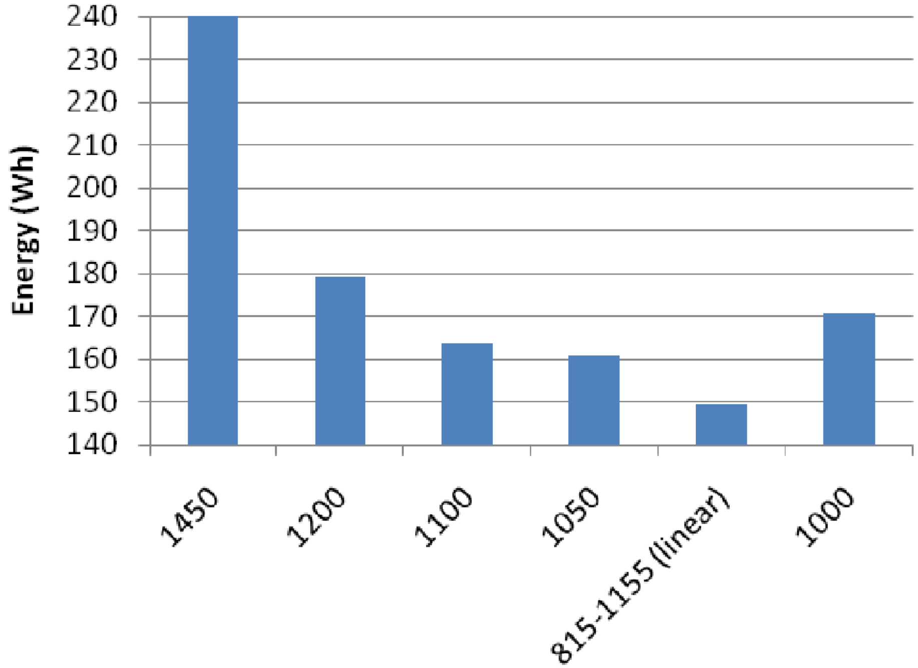


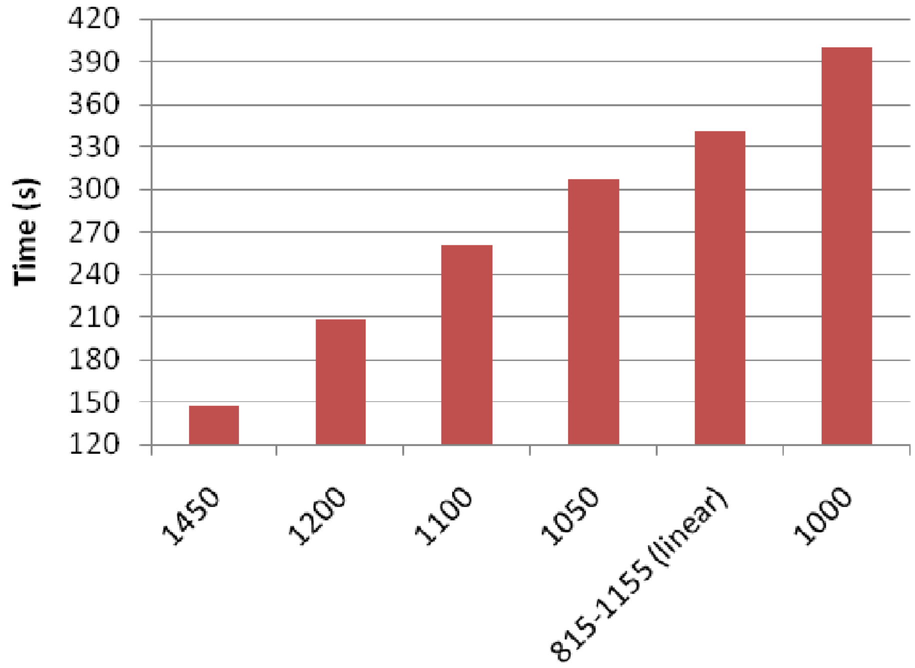




- Surrounding system and the pumping task are identified during the first run
- E_s charts (curves) are determined for $H_{st,1}$ and $H_{st,2}$ cases
- Rotational speed profile is formed with the E_s chart information

Simulation results for a reservoir filling application





- System: H_{st}=5-10 m, k=0.0149, 3.75 m^3 per reservoir filling
- Pump: Sulzer APP22-80, 1450 rpm
- Minimum energy consumption is achieved with the linear speed profile

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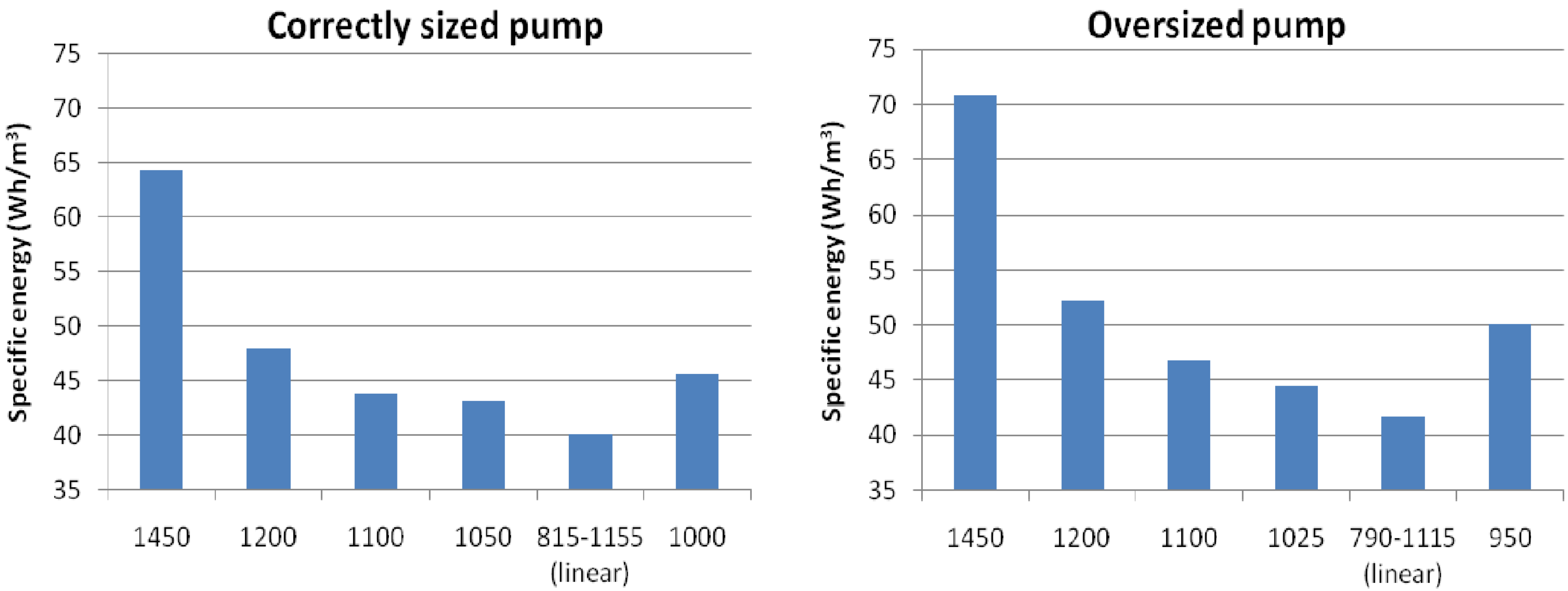
Compensation of an oversized pump with variable-speed usage



- Pump: Sulzer APP22-80 with a larger impeller resulting in a 5-10 % higher output than needed
- Difference in E_s is at smallest around 1050 rpm

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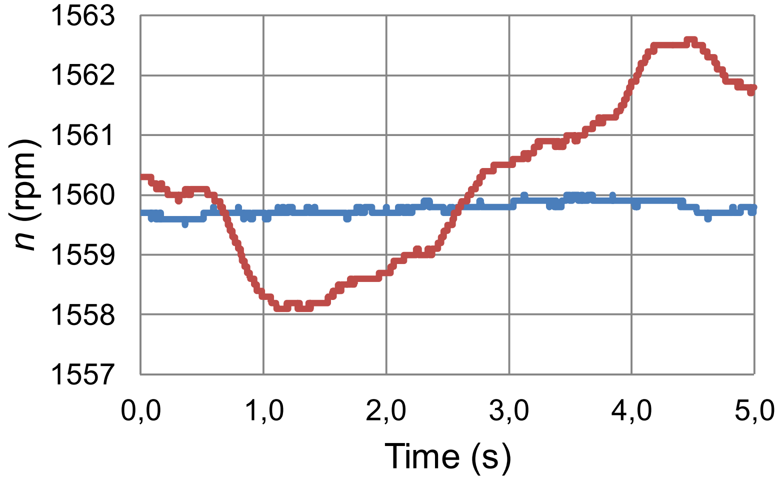
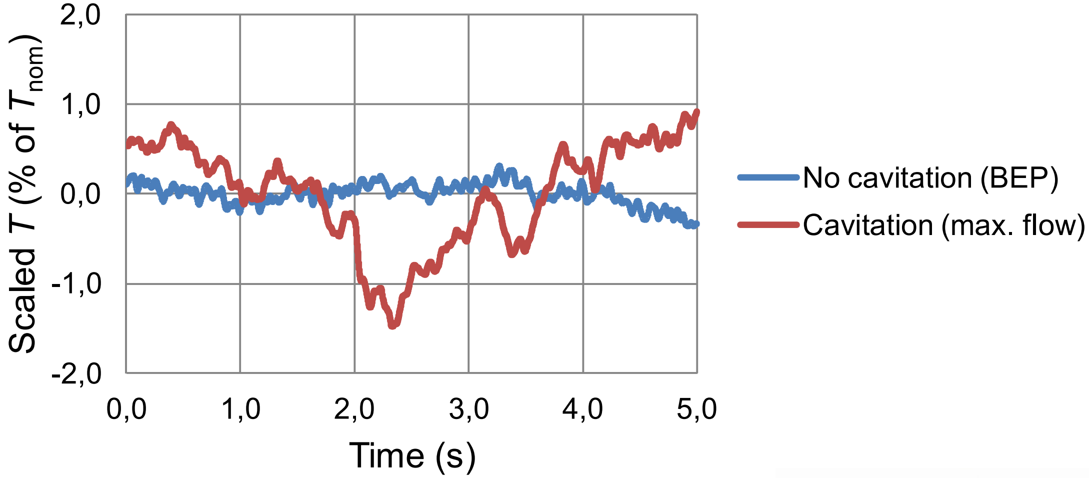
Part V: Identification of operational states that reduce the system lifetime or cause an immediate failure

Pump cavitation and fluid recirculation, fan stalling





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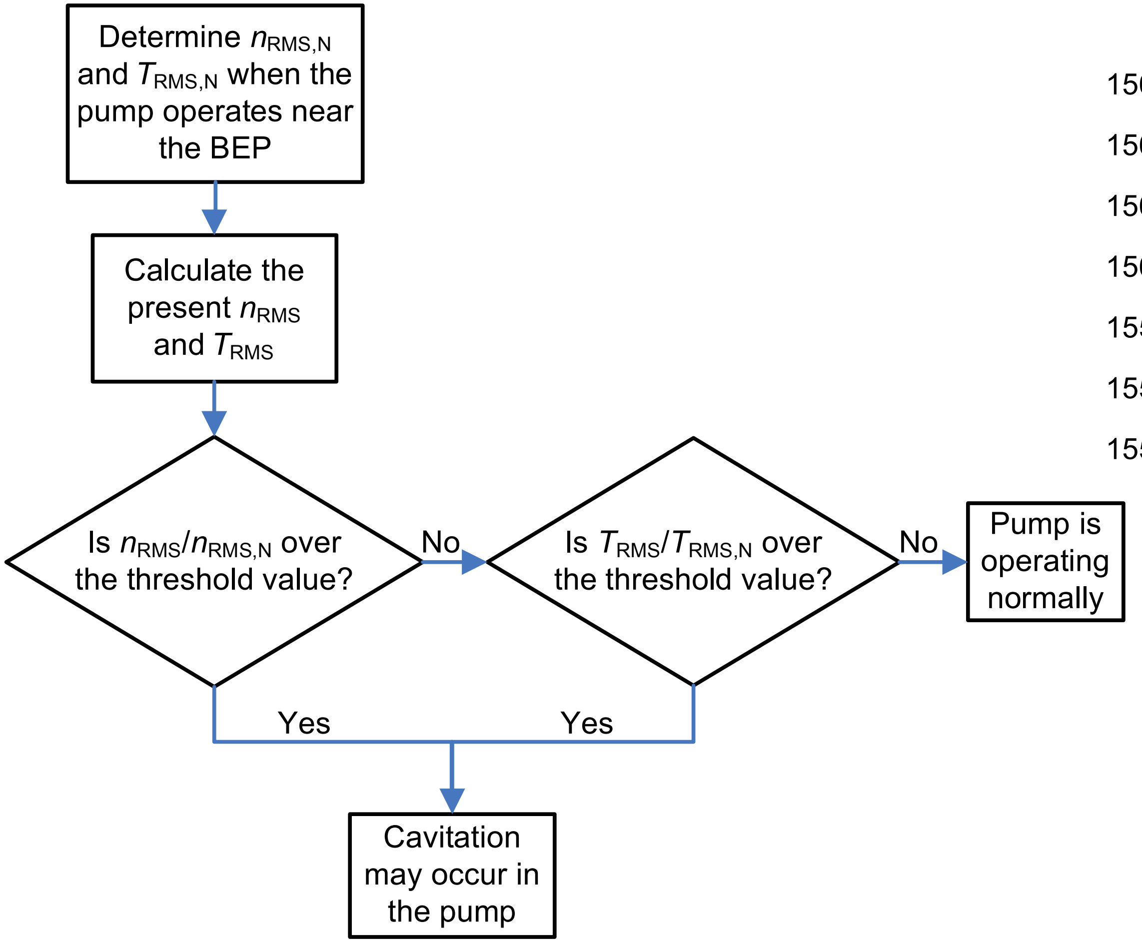
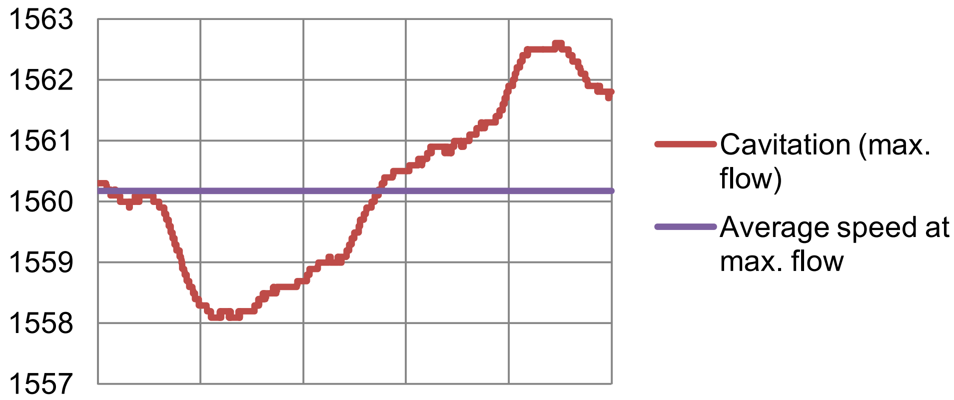
Frequency-converter-based, sensorless detection of cavitation or stalling





$$x_{DC}(n) = \frac{1}{M}\sum_{k=0}^{M-1} x(n-k)$$

$$x_{AC}(n) = x(n) - x_{DC}(n)$$

$$x_{RMS}(n) = \sqrt{\frac{1}{M}\sum_{k=0}^{M-1} x_{AC}^{2}(n-k)}$$

Ref.: T. Ahonen et al., "Novel method for detecting cavitation in centrifugal pump with frequency converter," *Insight,* vol. 53, no. 8, August 2011.

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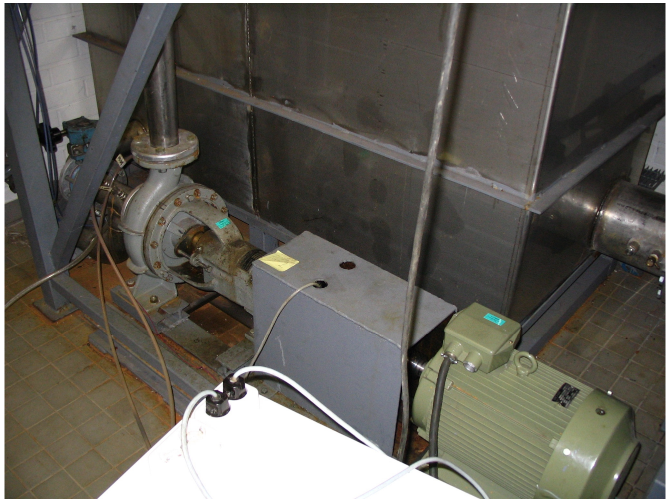
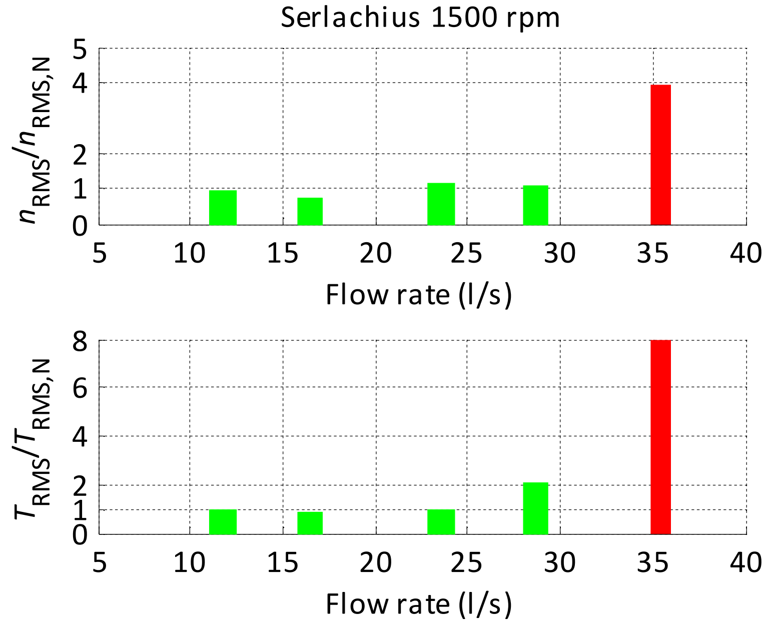
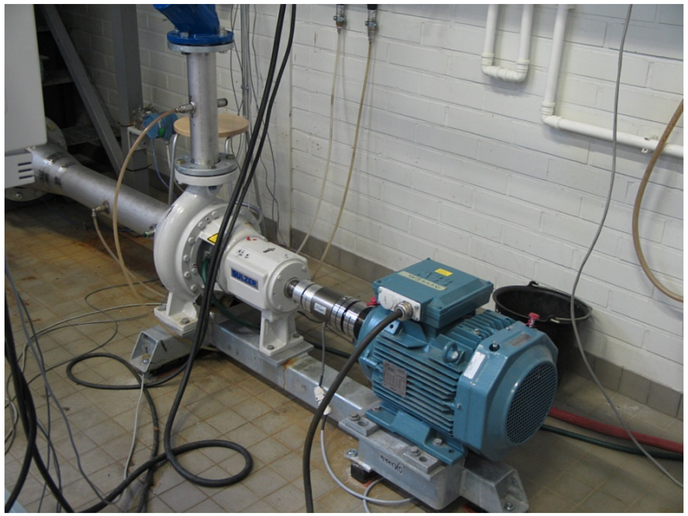
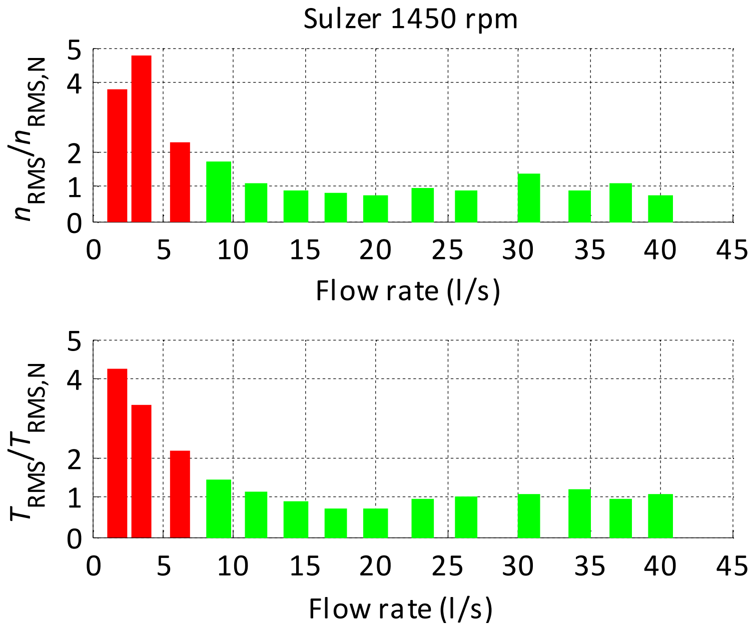
Test results



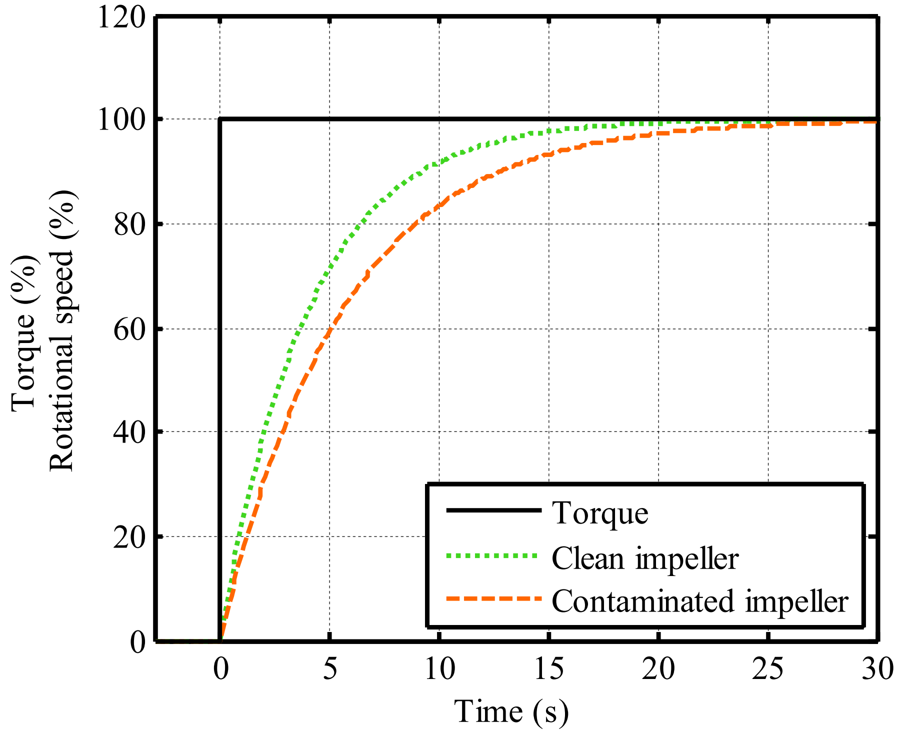


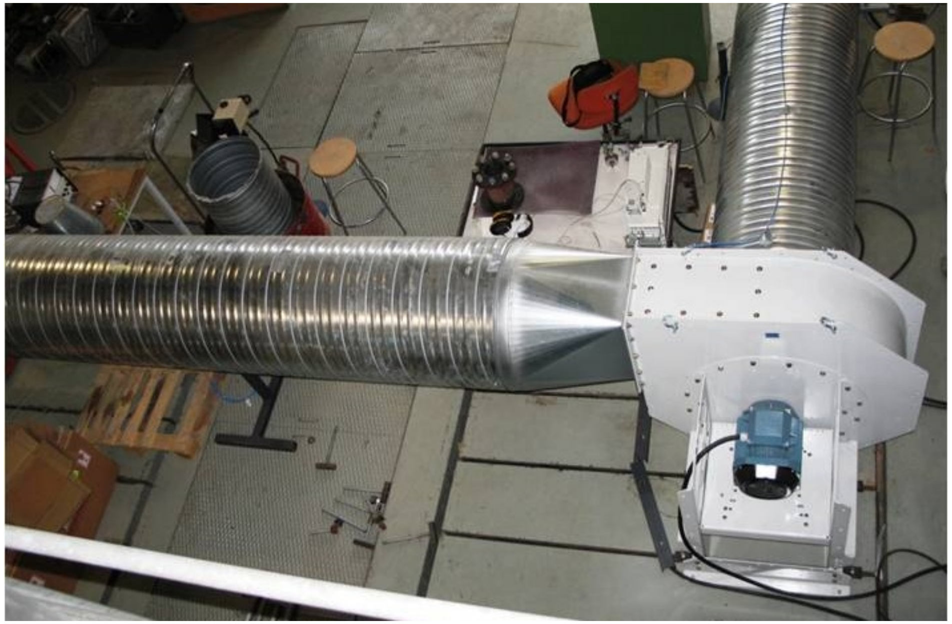




Detection of contamination in a fan impeller

- Impeller contamination is a root cause for several imbalance- and vibration-related faults in fans





Ref.: J. Tamminen et al., "Detection of Mass Increase in a Fan Impeller with a Frequency Converter," *IEEE Trans. on Ind. Electron.,* Digital Object Identifier: 10.1109/TIE.2012.2207657, 2012.

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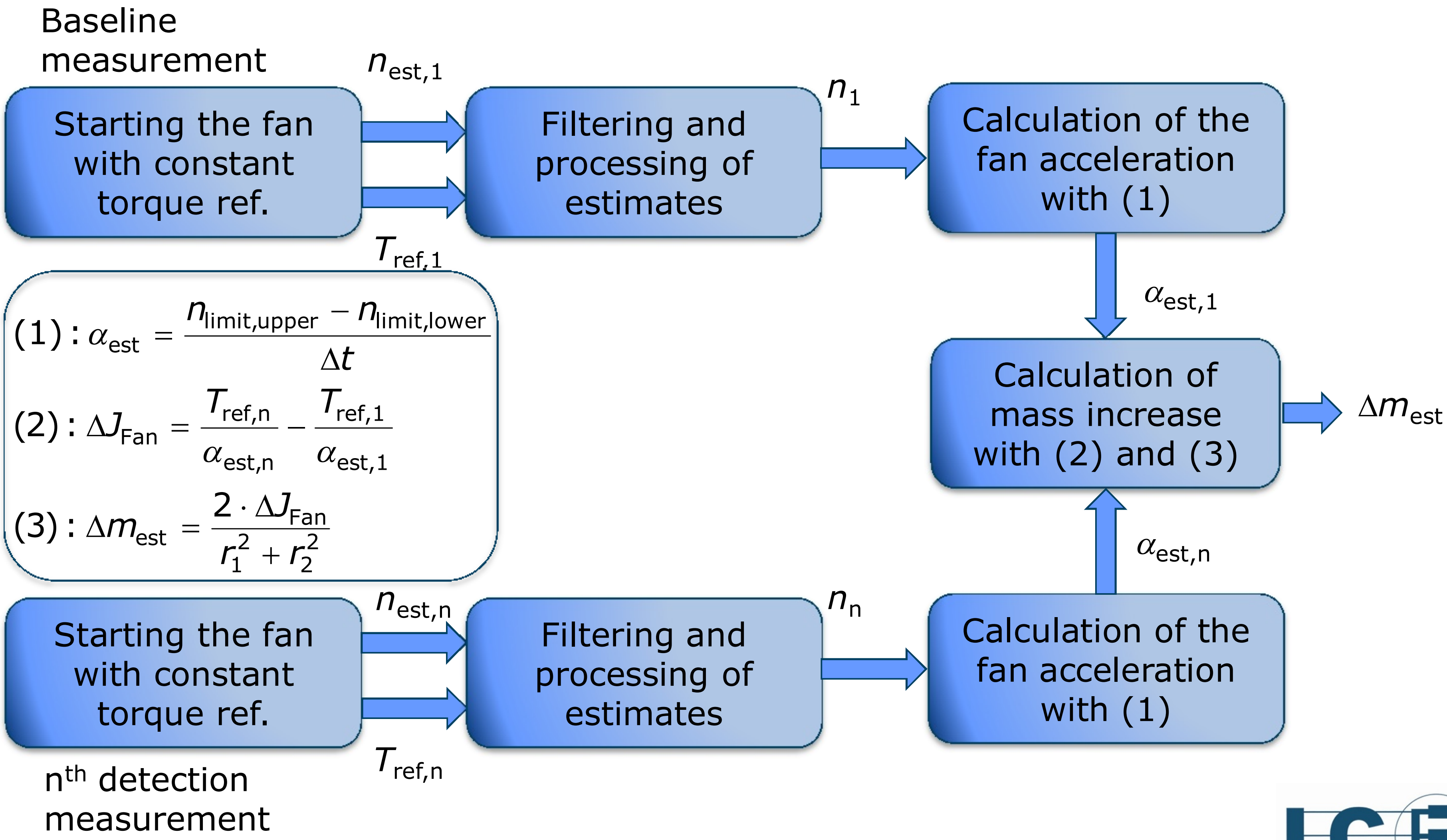
Operation of the fan impeller contamination detection algorithm



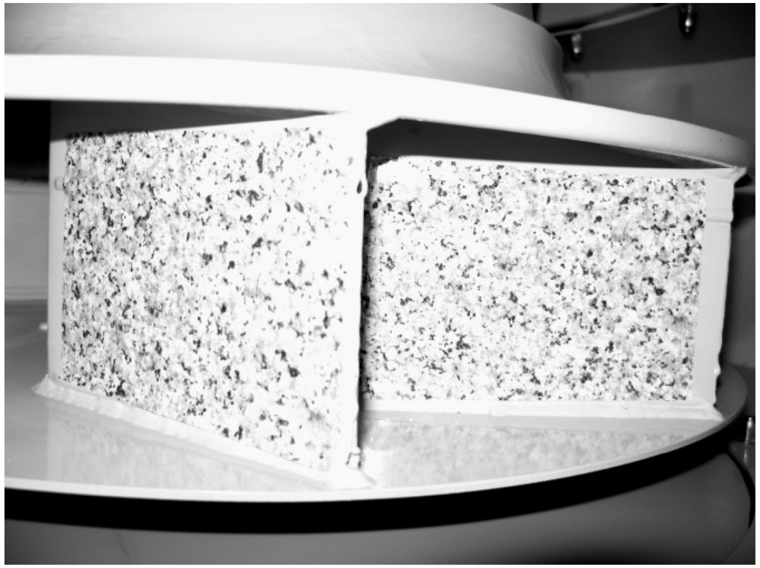
$$(1): \alpha_{est} = \frac{n_{limit,upper} - n_{limit,lower}}{\Delta t}$$

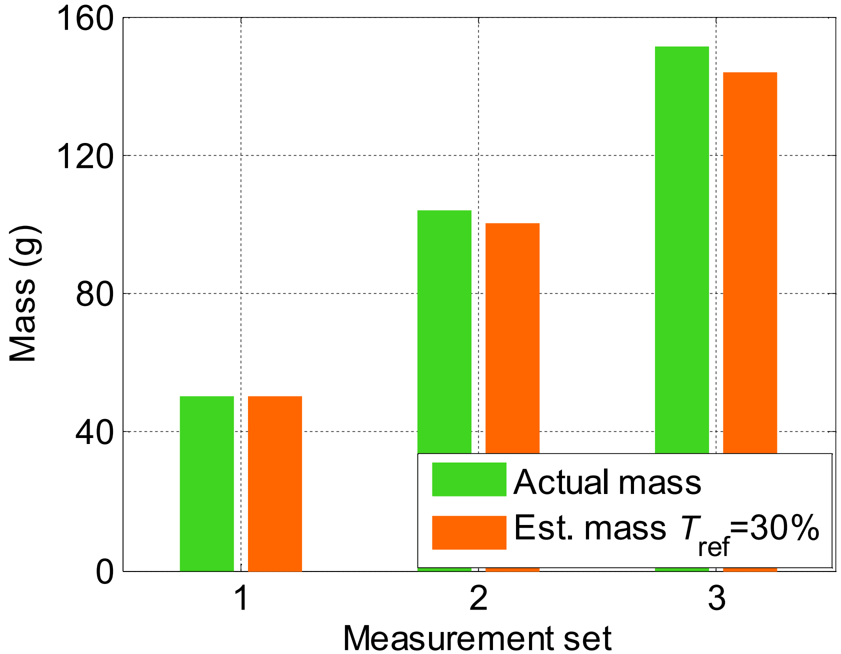
$$(2): \Delta J_{Fan} = \frac{T_{ref,n}}{\alpha_{est,n}} - \frac{T_{ref,1}}{\alpha_{est,1}}$$

$$(3): \Delta m_{est} = \frac{2 \cdot \Delta J_{Fan}}{r_1^2 + r_2^2}$$

Test results

- Method has been successfully verified by laboratory measurements





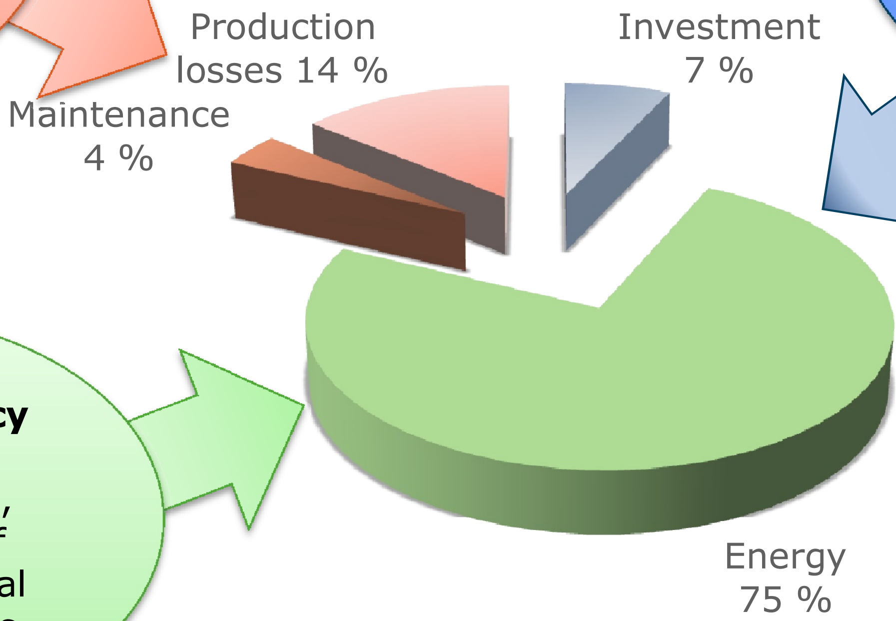
Ref.: J. Tamminen et al., “Detection of mass increase in a fan impeller with a frequency converter,” *IEEE Trans. on Ind. Electron.,* Digital Object Identifier: 10.1109/TIE.2012.2207657, 2012.

Summary

Role of the frequency converter in LCC optimization of pump and fan systems

Detection of operational states degrading system lifetime: cavitation, stalling, recirculation, dry-running, contamination build-up, etc.

System performance monitoring: On-line specific energy consumption estimation, wear and air filter contamination detection, etc.



Energy efficiency optimization: parallel pumping, compensation of oversizing, optimal speed profiles, etc.

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Main points

I. Frequency converter is a versatile tool with monitoring and diagnostic abilities

II. Sensorless pump and fan system operation estimation is possible with dedicated models

III. Frequency converter by itself does not realize energy efficient system operation

IV. Identification of adverse operational states can effectively decrease the risk of system faults