Extremum-seeking control of anaerobic digestion systems under fuzzy logic supervision

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Outline

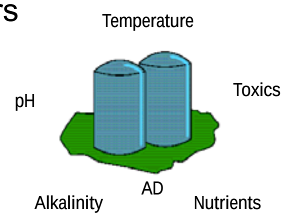
- Introduction
- Objective
- Controller realization
- Performance analysis
- Conclusions

Introduction

- Anaerobic digestion
  - Degradation of organic material to CH_4 and CO_2
  - Cost-effective solution for the treatment of industrial wastewaters

But…

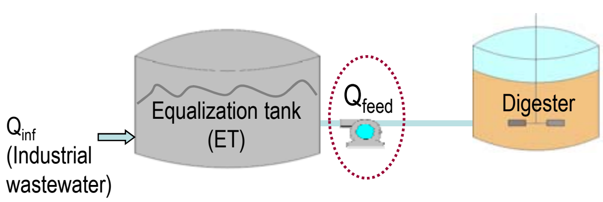
  - Instability and high sensitivity to overloads and disturbances…



Necessity of monitoring and control strategies

Introduction

- Monitoring and control in AD
  - Objective: stability, efficiency, max. CH_4 production
- Instrumentation and handles:
  - On-line "key" variables: pH, Qgas, $\%CH_4$
  - Influent flowrate to the reactor (Q_{feed})



Introduction

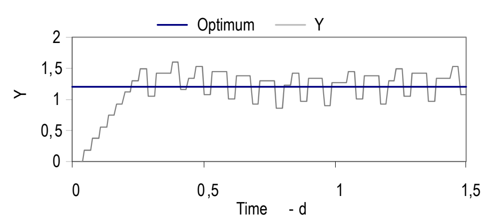
- Control strategies in AD
  - Validations only in lab and pilot-scale plants.
  - Restrictions in Q_{feed} are not considered.
  - Effects of ET are no considered.

⇩

Necessity to study the implications of including ET in a full-scale scenario

Introduction

- Extremum-seeking (E-S) controllers
  - Maximize or minimize an objective function.



  - In AD: applied to maximize the CH_4 production.

⇨ max. CH_4 = max. Q_{feed}

Introduction

- Extremum-seeking (E-S) controllers

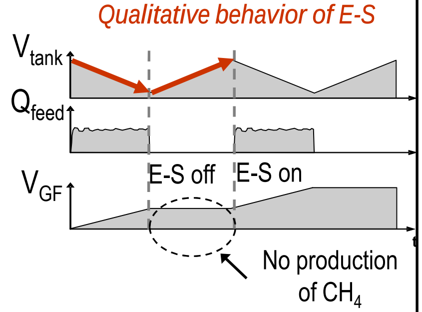
….Restrictions in a full-scale plant with ET

- Treated volume
- Volume of ET

… Max. CH_4 ⇒Q_{feed} ↑↑ ⇒ Vtank ↓ ⇒ emptying of ET

… Conservative strategy ⇒ Q_{feed} ↑ ⇒ overflowing of ET

Qualitative behavior of E-S



Introduction

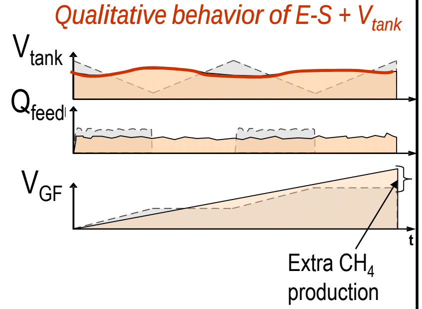
- Extremum-seeking (E-S) controllers

….As a result:

Importance of combining E-S with additional algorithms:

- Automatic regulation of Q_{feed} and CH_4 as a function of ET
- A more continuous feeding

Qualitative behavior of E-S + V_{tank}



Objective

- Model-based design and validation of a controller that combines:
  - an E-S algorithm
  - exploiting the hydraulic capacity of ET

  to regulate the CH_4 production

  … trade-off between CH_4 production and process efficiency
- Limitations
  - Non-linear problem
  - Hydraulic capacity in ET
  - Set-point adjustment ✗ Dynamical optimization ✓

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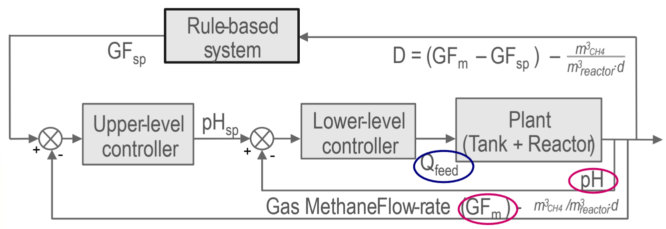
- Conclusions

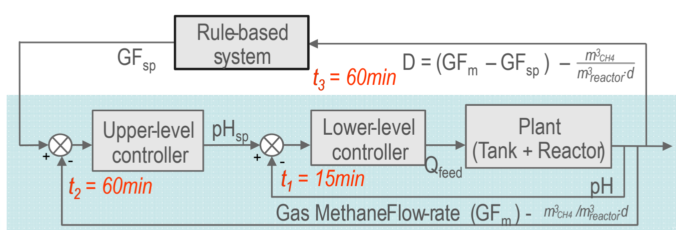
Controller realization

- STEP 1. Previous E-S controller - LC
  - Reference: Liu et al., (2004, 2005)
  - Objective:To maximize the CH_4 production and rejection of disturbances.
  - On-line measurements: pH and CH_4 gas flow (GF_m)



Controller realization

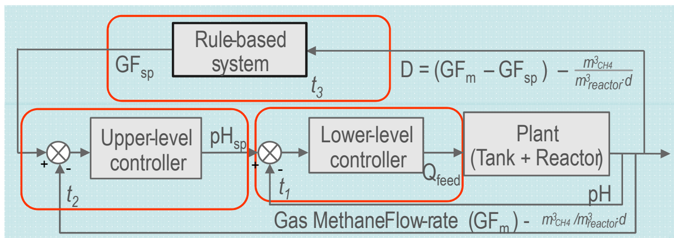
- STEP 1. Previous E-S controller - LC



1 Cascade scheme: simple P loops → $u(k) = u_0 - K_p \cdot e(k)$

Controller realization

- STEP 1. Previous E-S controller - LC



① Cascade scheme: simple P loops

- Lower Controller → At t_1, sets Q_{feed} as function of the error $(pH_{sp} - pH)$
- Upper Controller → At t_2, sets pH_{sp} as a function of the error $(GF_{sp} - GF_m)$

② Rule-based system: At t_3 sets GF_{sp} as a function of D $(GF_m - GF_{sp})$

Controller realization

- STEP 1. Previous E-S controller - LC

② Rule-based system

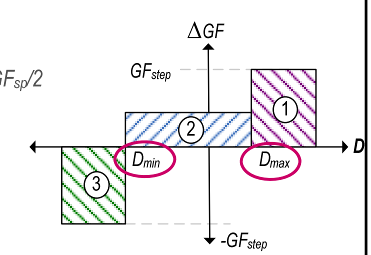
- Observer of the digester's state ("D")
- D_{max} and D_{min}: determine the operational areas for D
- ΔGF increment to GF_{sp}:

① If $D > D_{max} \rightarrow GF_{sp(i)} = GF_{sp(i-1)} + \Delta GF_{sp}$

② If $D_{min} < D < D_{max} \rightarrow GF_{sp(i)} = GF_{sp(i-1)} + \Delta GF_{sp}/2$

③ If $D < D_{min} \rightarrow GF_{sp(i)} = GF_{sp(i-1)} - \Delta GF_{sp}$

D_{max} and D_{min} → force that pushes the process towards a higher or lower GF_m

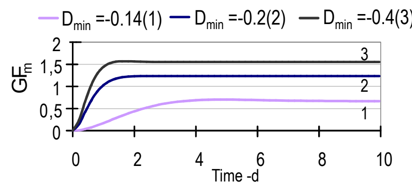


Controller realization

- STEP 1. Previous E-S controller - LC

(2) Rule-based system

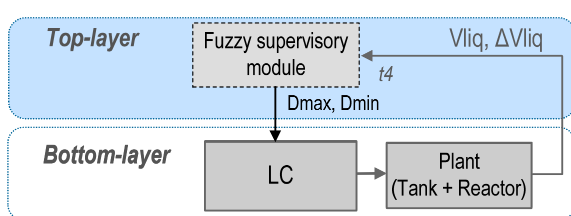
- Small values of D_{min},D_{max} promote higher GF_m and faster responses
- D_{max},D_{min} could be tuned to promote different GF_m



Online adaptation of D_{max}, D_{min} as a function of the state of ET

Controller realization

- STEP 2. Proposed controller – FLC
  - Bottom-layer: LC controller
  - Additional Top-layer: automatically regulation of D_{max} and D_{min} as a function of the hydraulic capacity in ET

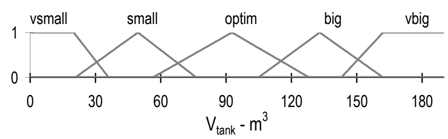


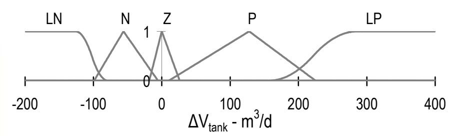
Controller realization

- STEP 3. Fuzzy module design

  Selection of inputs, outputs, set of rules…

  - Two inputs: V_{tank}, ΔV_{tank}





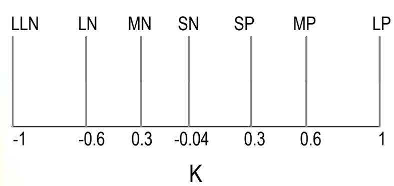
LN: Large negative,
N: negative…

Controller realization

- STEP 3. Fuzzy module design

  Selection of inputs, outputs, set of rules…

  - One output: K [-1 1]

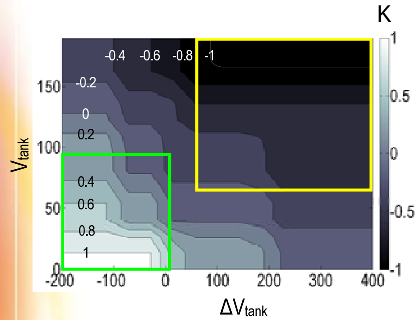


Adaptation law with an incremental structure:

$$D_{min}(t) = D_{min}(t-1) + K * \Delta D_1$$
$$D_{max}(t) = D_{max}(t-1) + K * \Delta D_2$$

Controller realization

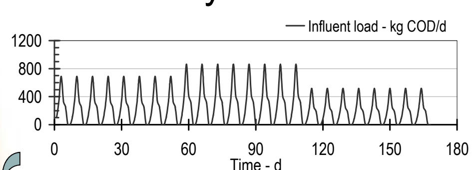
- STEP 3. Fuzzy module design
  - I/O mapping



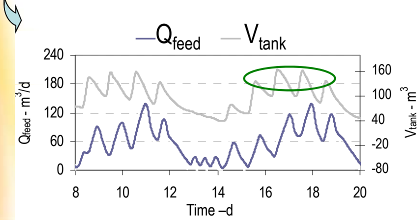
- High values in V_{tank} and ΔV_{tank}
  $\Rightarrow$ high negative value of K
  $\Rightarrow$ higher Q_{feed} values
- Low values in V_{tank} and ΔV_{tank}
  $\Rightarrow$ high value of K
  $\Rightarrow$ lower Q_{feed} values.

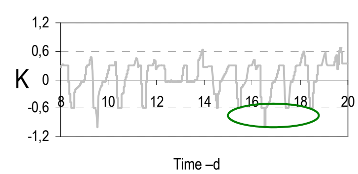
Performance analysis

- FLC with dynamic influent



… 6 months of realistic industrial wastewater



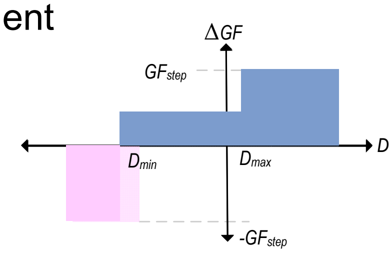


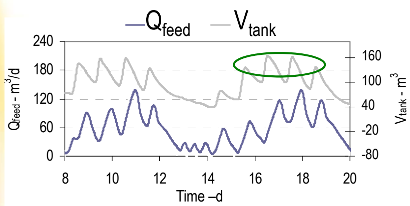
Performance analysis

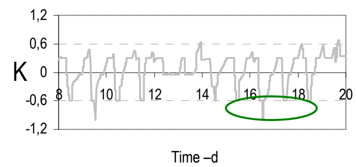
- FLC with dynamic influent

Remember that…

$$D_{min}(t) = D_{min}(t-1) + K * \Delta D_1$$
$$D_{max}(t) = D_{max}(t-1) + K * \Delta D_2$$

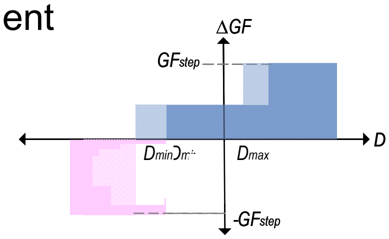


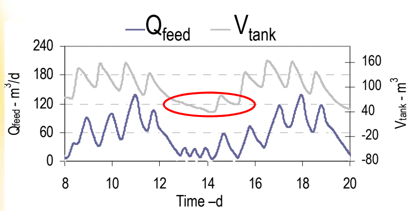


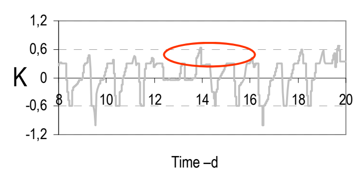


Performance analysis

- FLC with dynamic influent







Performance analysis

- Systematic study

			CONTROL STRATEGY		
Index	Acronym	Units	OL	LC	FLC
Effluent Quality	EQI	*Kg pollution/d*	386	+ 8%	+13%
COD Removal Efficiency	REf	*%*	59	+ 6%	+8%
Unitary Methane Production	UMp	*Nm^3CH_4/m^3_{raw} WW*	0.74	+ 6%	+8%
Energy Recovery	EnR	*kWh/d*	415	+ 6%	+8%
External alkalinity		*Kg $CaCO_3$/d*	79	-	-

- LC controller
  - Indexes are improved in comparison to OL without addition of alkalinity
  - EQI improves by about 8%. REf, UMp y EnR improve by about 6%

➡ Operational and economics benefits with LC

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Performance analysis

- Systematic study

			CONTROL STRATEGY			
Index	Acronym	Units	OL	LC	FLC	
Effluent Quality	EQI	*Kg pollution/d*	386	+ 8%	+13%	= + 21%
COD Removal Efficiency	REf	*%*	59	+ 6%	+8%	= +14%
Unitary Methane Production	UMp	*Nm^3CH_4/m^3_{raw} WW*	0.74	+ 6%	+8%	
Energy Recovery	EnR	*kWh/d*	415	+ 6%	+8%	
External alkalinity		*Kg $CaCO_3$/d*	79	-	-	

- FLC controller
  - Indexes are improved in comparison to LC without addition of alkalinity
  - EQI improves by about 13%. REf, UMp y EnR improve by about 8%

➡ Important operational and economics benefits with FLC

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Conclusions

- The E-S controller (LC) on bottom layer guarantees a good disturbance rejection.
- On-top, the fuzzy supervisory module optimizes the long-term operation based on the state of the equalization tank.
- Compared with manual operation, the FLC strategy reaches improvements of 14-21% on <u>ALL</u> performance indexes.
- These results stimulate the interest for further implementation of the proposed controller in industry.