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Analysis of first field results of the improved model based qualitative fault detector for a central air handling unit (CAHU)

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Introduction

The model based qualitative fault detector for a central air handling unit that was developped in the Annex 25 [1] has been implemented on a substation of the building energy management systems (BEMS). It has been programmed as a first version I in COLBAS, the Landis & Staefa proprietory language and has been running on-line as a prototype for two years. Experiences made during the first year led to a new improved version II of the detector [2]. First results with version II will be reported. The paper is organized along the agreed template

Test building, plant and control system

The test building is the Sennweid office building of Landis & Staefa Switzerland near Zug, Switzerland.There is one central air handling unit (CAHU) for the conditioning of the air supplied to the different zones. The CAHU is controlled by a substation of the VISONIK system. Temperatures, humidity and differential pressure are controlled by the system. For the application of the fault detection scheme only the temperature control is considered at the moment.

Intended end-user

In its simplest form the detector will be implemented as a new optional function block on the level substation. It will run on-line and generate alarm signals. These alarm signals can be stored momentarily in the substation together with other alarm messages and/or they can be transmitted to the central station of the BEMS. There they can be stored again together with all the important signals in order to analyze the alarms off-line. As the alarms are not critical, the interpretation of the results can be done mostly off-line. The intended end user of the fault detection scheme is either the operator or the HVAC service engineer. The owner of the building is only interested if one can show him the saved costs if particular faults can be eliminated. This involves more than just the functionality offered in this implementation.

Faults to be identified

A fault detection and diagnosis system deals with two kind of faults: **1) faults or symptoms found during the detection of underperformance** (e.g. discrepancies in control variables) **and 2) faults found in the diagnostic part where a search for the causes (faulty behaviour of parts of the system) of the observed underperformance is done** (e.g. blocked valve). The used method here detects faults by comparing quantized measured controller ouputs with quantized model based predicted controller outputs in steady state. Thus, any discrepancies in the control signals for heating, heat recovery and cooling generates an alarm. The discrepancies can occur for one. two or all three control variables. The model based predicted controller outputs describe the nonfaulty, energy optimal correct steady state behaviour of the controlled plant.

What faults causing the above detected discrepancies can be found with this method ? The answer to this question depends on how much a priori information is used. In its simplest form, the most qualitative one, only a very restricted number of faults can be detected. They include sensor, valve (damper) and control faults. Example:

- sensor offsets
- simultaneous heating and cooling caused by blocked valve or damper
- nonoptimal control of heat recovery wheel

Some faulty behaviour can be detected only under specific operating conditions. Attempts to analyze such situations were made in earlier works [3], [4] and [5]. Most of the obtained results depended however on too detailed information of the controlled system so that it could not be exploited in practical situations up to now. It is highly probable that due to the coarse information used in the qualitative detection scheme, a single cause cannot be found for an observed faulty behaviour. A list of faults that can possibly be found as causes for certain discrepancies has yet to be investigated.

Sensors used

It is one of the strength of this method that **no additional sensor is needed.** Only the temperatures that are used anyhow for the control of the plant are needed for the detection of discrepancies.

FDD method

The model based qualitative fault detection method has well been described in previous publications [1].

Design data used

Design data information can be classified into the following classes:

1) parameters of components (e.g. heat transfer coefficient, geometrical data, maximal power of heater)
2) Specific operation points (e.g. nominal mass flow, inlet temperature)
3) topological information of the system (e.g. which sensor does what and is located where)
4) BEMS naming and adressing (point names)
5) control parameters (e.g. PI parameters, set points, operation mode, scheduler, dead zones, hysteresis)

It has also to be distinguished, whether these data are needed for the model itself, for the steady state detector, for the fault detection thresholds or for the diagnostic part.

For the **qualitative model** used in the method **only a few topological data** (class 3)) are needed.

For the **steady state detector**, which is needed as a preprocessing unit for the fault detector, some information of class 1) and 2) are needed. The component parameters needed are [6]:

- maximal heating, cooling and heat recovery power
- time constants of heater, cooler and heat recovery or knowledge about the PI control parameters

Specific operating points conditions needed are:

- nominal air flow

Regarding the information needed for the **threshold selection** see in a later section with this title.

For the **proper operation of the fault detector** *several control specific parameters* must also be known:

- operation mode
- scheduler
- dead zone between heat recovery and cooling
- *hysteresis for reverse operation of the heat recovery wheel*
- sampling time

For the **diagnostic part** as it is used now and which is not very powerful , no additional information is needed. To improve the diagnosis more information must be used (which is fault dependent).

Training data required

Another strength of this method is that ***no training data are required*** (except for the threshold selection)

User interface

The on-line part of the detector running on the substation is hidden from the user and must be parameterized during the commissioning phase. This includes the configuration of the correct data points. If a central station of the BEMS is available, the actual state of the detector is displayed on the screen [2]. Parameters of the detector can then be changed on-line.

The off-line part, that means analyzing the alarm situations, is not automated up to now. A snapshot of all the temperatures, control outputs and fault detector outputs is stored for each alarm together with a time stamp. This information can be printed by the operator whenever he wants. The relevant time series can additionally be stored in a separate data base, from where they can be later reloaded in order to verify certain situations.

User selected parameters

The user must select the parameters listed in Table 1. They are divided into four categories:

The steady state detector needs 8 parameters. It is possible reduce this number, if only the most critical temperature and control variable is considered as the only relevant quantities for steady state conditions.

All threshold parameters of Table 1 can be changed on-line from the central station of the BEMS. With this capability the operator can influence by himself the thresholds. That allows him to control the number of alarms (false or right alarms).

Steady state detector:	time constant Tss		
11 parameters	thresholds of temperature variances		
	ΔVarTr	ΔVarTs	ΔVarToa
	thresholds of control variances		
	ΔVarUh	ΔVarUc	ΔVarUd
	3 thresholds for oscillations		
	Delay (hysteresis)		
transformation:	control thresholds		
4 parameters	Ucmin, Uhmin, Udmin, Udmax		
zone predictor:	zone boundaries (thresholds)		
3 parameters	dx,dy.dz		
model uncertainties	*fans as heat sources (temperature increase/decrease)*		
2 parameters	ΔTr, ΔTs		

Table 1: user selected parameters

Threshold selection method

Thresholds have to be selected for the steady state detector and for the fault detector. The thresholds are dependent on the following components:

1) **measurement** uncertainty: specified by sensor type
   example: temperature typical +/- 0.2 degrees

2) *uncertainty in reaching* **steady state**: *estimated by using simplified models of the* controlled process

3) **modelling** uncertainty: dependent on the actual installation; where are the sensors located, how are ducts laid out, what is neglected in the models?

This uncertainty is most critical and plant specific

For the selection of the **steady state** thresholds, the following information must be obtained through observations and historical data:

- variation (noise) on sensor signals (measurement uncertainty)
- residual effect of step changes of set point and outdoor air temperature. The maximum heights of the steps must be chosen (uncertainty reaching stead state)

For the selection of the fault detector thresholds the modelling uncertainty has to be added to the above effects. For the choice of this component one needs observations and historical data too

Results of trials

In [2] several implemented improvements of version I to version II were reported. These improvements included:

scheduler information used
number of thresholds reduced
steady state detector for controller output
detection of oscillating controller output
thresholds for control variables
including modelling uncertainty
recording of alarms, false alarms, statistics, documentation

The reduction of the number of thresholds for the zone predictor part of the fault detector resulted in the zone diagram of Fig.1 and its corresponding control combinations of Table 2:

From October 97 three time periods were analyzed of the implemented version II of the fault detector. The statistics are the following:

	12.10.97-12.12.97	13.12.97-23.3.98	24.3.98-28.5
		lower FDD(zone) thresholds	-->
FDD on	528h	792h	560h
in SS	422h *(80%)*	702h *(89%)*	495h *(89%)*
reaching SS	158 times (3/d)	217 times (3/d)	424 times (6/d)
alarms	not available at the moment		**128 alarms**

Analysis of the alarms:

The time the controlled system is in steady state is pretty constant, 80-90% of the operating time of the detection scheme. During the spring season the time the system remains in a steady state is roughly half as long as during the winter season due to more sudden changes in outdoor conditions.

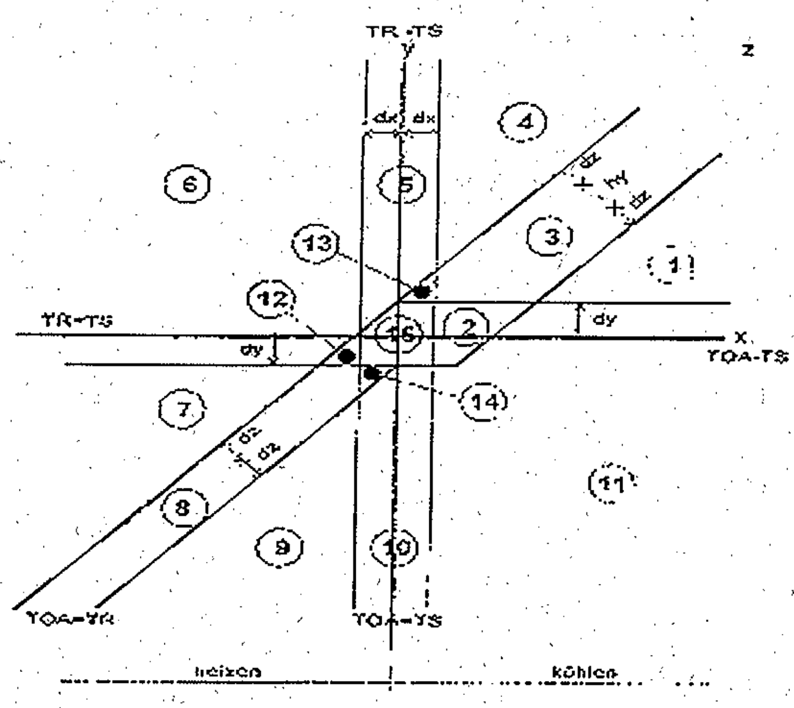

Fig. 1: Zone diagram with reduced number of thresholds

Bild-Darstellung

Befehl Anwahl Funktionen Anlagenbeschreibung

Zustände der Zonen

PLT.PSTA	PrLE	PrWRG	PrLK
Zone 1	CLO	MAX	NCLO
Zone 2	CLO	OFF	NCLO
	CLO	MAX	NCLO
	CLO	MAX	CLO
	CLO	BETW	CLO
Zone 3	CLO	OFF	NCLO
	CLO	MAX	NCLO
Zone 4	CLO	OFF	NCLO
Zone 5	CLO	BETW	CLO
	CLO	MAX	CLO
	NCLO	MAX	CLO
	CLO	OFF	CLO
	CLO	OFF	NCLO
Zone 6	CLO	BETW	CLO
	CLO	MAX	CLO
	NCLO	MAX	CLO
Zone 7	NCLO	MAX	CLO
Zone 8	NCLO	MAX	CLO
	NCLO	OFF	CLO
Zone 9	NCLO	OFF	CLO
Zone 10	NCLO	OFF	CLO
	CLO	OFF	CLO
	CLO	MAX	NCLO
	CLO	MAX	CLO
	CLO	BETW	CLO
Zone 11	CLO	MAX	NCLO
	CLO	MAX	CLO
	CLO	BETW	CLO
Zone 12	CLO	BETW	CLO
	CLO	MAX	CLO
	NCLO	MAX	CLO
	NCLO	OFF	CLO
Zone 13	CLO	OFF	NCLO
	CLO	OFF	CLO
	CLO	BETW	CLO
	CLO	MAX	CLO
	CLO	MAX	NCLO
	NCLO	MAX	CLO
Zone 14	CLO	OFF	CLO
	CLO	BETW	CLO
	CLO	MAX	NCLO
	CLO	MAX	CLO
	NCLO	OFF	CLO
	NCLO	MAX	CLO
Zone 15	alle	alle	alle

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Table 2: Control combinations of the 15 different zones

PrLE: prediction of quantized heater control signal
PrWRG: prediction of quantized heat recovery control signa
PrLK: prediction of quantized cooling control signal

The analysis of the alarms showed the following situations:
1) 60 of the alarms lasted only a very short time (1-3min). The reason for this is not clear. By introducing a delay one can suppress these kind of alarms.
2) 38 alarms showed a control combination where all control signals are off or closed in many different zones. The reason for the occurrence of these alarms are twofolded:
- the threshold between closed and on for valve resp. between off and between for the heat recovery control output is too high
- an energy free band is not yet implemented
3) That leaves **10 alarms** unaccounted for occuring in 5 zones with three wrong control combinations.Whether these alarms are false alarms or not, is not clear at the moment. Some are caused by a two big discrepancy between actual and averaged values

Improvements

Improvements of the situation as it is now will be done in the following directions:
introduction of an energy free band
introduction of minimum time of fault persistence
lowering the thresholds for the quantization of the control variables
use of actual values only (no mixing between actual and averaged) for the zone and transformation part of the fault detector
better way to include modelling uncertainties

Introducing temperature sensor offset

Temperature measurements fall into two categories:
1) The measurement of the supply air temperature which is the variable to be controlled. An offset of this sensor has the same effect as a changed setpoint of the supply air temperature. It cannot be detected directly by our method. If the setpoint of the supply air is cascaded with the zone temperature, a tracking of the setpoint might identify this cause. If the the setpoint is not cascaded an increase-/decrease of the zone temperature will lead to a similar change in the return air temperature. So it might be possible to identify the cause via the return air temperature.
2) The measurements of the outdoor air temperature and the return air temperature. Both are actually disturbances on the control loop and are used only for the reverse operation of the heat recovery wheel. An offset in one of these sensors can be detected in certain operating regions. As long as the temperature operating points with and without offset are not separated by the Tr=Toa line in the zone diagram, it might be possible to detect the offset.

Experiments and results are still preliminary on this subject and will be reported at a later date.

Satisfaction of user requirements

At the moment it is too early to say whether the detector will fulfill market needs.

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