Implementation of PFC (Predictive Functional Control) in a PLC (Programmable Logic Controller) for a HVAC (Heating, Ventilation and Air Conditioning) system

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Abstract. HVAC systems of industrial buildings consume a lot of energy. Therefore it is important to know the performance of these systems and strategies to optimize the hardware and the control. Tackling the temperature control of the HVAC system promises quick savings by tuning the control within specified tolerance limits, which mostly can be done by low investment. This paper mainly deals with the implementation strategy of a new controller in a PLC using the predictive functional control for temperature control. The different stages of the implementation from the simulation over the SCL code till to the real-time operation are presented. A bumpless switch between the PI(D) and the PFC control was realized, as well.

1. Introduction
When looking at the main consumer of an industrial site mostly the HVAC system could be addressed. The integration of an energy management to industrial management structures will be more and more interesting to handle all processes which are related to the energy consumption and costs. Beside the acquisition of significant energy data, methods have to be defined which can identify wasteful processes and present solutions which can optimize the performance of the related equipment to reduce the energy consumption, therefore costs and the CO₂ emissions. When tackling HVAC systems energy savings can be achieved either by implementing new modern HVAC devices, like a new high efficient ventilator, or to apply a better control of the actual HVAC devices. Latter task is solved with a lower investment. The premise is that the new control algorithm is more effective than the actual used one. Temperature records of the actual HVAC systems have shown that the existing PI(D) control sometimes is not optimal, because the prescribed temperature limits were often violated. Another problem was observed during the crossover from heating to cooling and vice versa, as often both heating and cooling was active for a short transition period. This phenomenon caused additional
energy costs. For this defective control a strategy was wanted, which keeps the temperature within the allowed limits and prevents a simultaneous working of heating and cooling.

We had two choices, either tuning PI(D) control better and using a dead zone or to apply a whole new control strategy which considers the physical processes of heating and cooling. It is known from the literature that predictive control is a model based control and therefore it is superior over PI(D) control. MPC (Model-based Predictive Control) has been implemented in hundreds of big process engineering plants like refineries and lead to cost savings and safety improvement in opposite to coupled PI(D) control. In such plants usually several variables and constraints are to be controlled to be handled by expensive MPC packages. In a HVAC system however there are only few controlled variables (temperature and humidity) and usually only the manipulated and controlled variables are limited. PFC (Predictive Functional Control) is optimal for this case. The big advantage against big multivariable MPC packages lies in the simplicity of the PFC algorithm which allows a direct implementation in a PLC (Programmable Logical Controller) or a DCS (Decentralized Control System).

The modernization of the HVAC control in our case is divided into two stages:
1. model building, design and simulation of PFC control on the model of the HVAC plant,
2. real-time implementation of PFC control (with backup PI(D) control).

Because of the technological aims and possibilities only temperature control has been designed and elaborated so far. The first realization was tested on a HVAC system with constant recirculation. The operator could select the controllers (PI(D) or PFC) and could change between the control modes. Different interfaces were defined to ensure the data transfer between the two control types. In this way a bumpless switch between the two controllers is possible. The configuration, parameterization and visualization of the new controller are described in the sequel.

Simulations have shown the advantage of variable recirculation flap control; see (Kreutz, et al., 2013). This work is in the simulation stage and the real-time realization has been started.

2. HVAC SYSTEM

The selected HVAC system consists of a mixing chamber in which the fresh air is mixed with recirculated air from the conditioned room. Following the sequence in Fig. 1 the air is heated or cooled depending on the difference of the mixed air temperature and the desired set-point. The conditioned air is directed into the room by a ventilator, a part is recirculated and another part is discharged into the atmosphere.

Fig. 1 shows a detailed PI (Piping and Instrumentation) diagram of the HVAC system.

![Fig. 1. PI(D) diagram of the HVAC system](image_url)
The measuring points are as follows. 01: ambient air temperature, 02: mixed air temperature, 03: air temperature after heater, 04: air temperature after cooler, 05: air temperature after ventilator, 06: room temperature, 07: heater fluid inlet temperature, 08: heater fluid outlet temperature, 09: cooler fluid inlet temperature, 10: cooler fluid outlet temperature, 11: mass flow heater fluid, 12: mass flow cooler fluid.

Fig. 2 and Fig. 3 show the flow, inlet and outlet temperature sensors placed on the heat exchangers of the HVAC system to balance the energy over the following enthalpy equation:

\[
P_{HE} = \dot{Q}_{HE} = \dot{m}_{\text{fluid}} \cdot c_{p,\text{fluid}} \cdot (\vartheta_{\text{fluid}\_\text{in}} - \vartheta_{\text{fluid}\_\text{out}})
\]

where

- \(P_{HE} = \dot{Q}_{HE}\): heating power
- \(\dot{m}_{\text{fluid}}\): mass flow of the heat exchanger fluid
- \(c_{p,\text{fluid}}\): specific heat capacity of the fluid
- \(\vartheta_{\text{fluid}\_\text{in}}\): inlet temperature of the heat exchanger fluid
- \(\vartheta_{\text{fluid}\_\text{out}}\): outlet temperature of the heat exchanger fluid

Fig. 2. Flow, inlet and outlet temperature sensors placed on the cooler

Fig. 3 shows the flow, inlet and outlet temperature sensors placed on the heater of the HVAC system.

Fig. 3. Flow, inlet and outlet temperature sensors placed on the heater
3. HVAC CONTROL

Fig. 4 shows the plot of a defective control behavior of a PI(D) controlled air handling unit coming from a sporadic data recording. This alternating heating and cooling result in a serious energy waste. The reason is not the sampling time (100 ms) but the bad tuning and switching strategy applied.

![Fig. 4. Alternating heating and cooling as a result of defective control](image)

This control scenario motivated to do an overall analysis of the control situation of the HVAC systems at site to compare the initial control situation with current operating modus, looking for potential to reduce the consumption of heating and cooling fluid. Based on the internal best practices of the HVAC systems known as floating set-point, reduced mode (e.g. night set up) and heat recovery (e.g. recirculation) the HVAC have been analyzed mainly on the focus to implement a controller on a floating set-point strategy for temperature control. Traditionally climate control is realized by PI(D) controllers. Heating and cooling are realized by means of heat exchangers. Control of heat exchangers is a well investigated topic. For example Bonivento et al. (2001) and Raul et al. (2013) compare classical PI(D) and modern model based predictive control of heat exchangers and show the advantage of predictive control. Bonivento et al. (2001) and Chalupa et al. (2010) apply GPC (Generalized Predictive Control). However PFC (Predictive Functional Control) is an easier realizable predictive control as no numerical optimization is necessary even when considering manipulated variable limits (Richalet and O’Donovan, 2009). As a lot of PFC application has been already used successfully in the industry (see e.g. Abdelghani-Idrissi et al., 2001; Arbaoui et al., 2007), PFC was selected for temperature control in this application.

4. MATHEMATICAL MODEL OF THE PLANT

A HVAC consists of the following parts: (1) air mixing chamber (2) cooler/heater and (3) room, whose temperature is to be controlled. Fig. 5 shows the scheme of a heat exchanger (heater or cooler). For simplicity both cases are treated together in a uniform way.

![Fig. 5. Heater or also cooler](image)

Both the heater and the cooler are heat exchangers. The following notations are used:

\[ \theta_{\text{air in}}(t) : \text{inlet air temperature}, \quad \theta_{\text{fluid in}}(t) : \text{inlet temperature of heating or cooling fluid}, \]
The heat exchange process can be divided into two parts (Fig. 6):
- static part: symbolizing the stationary heat exchange process.
- dynamic part: symbolizing the time required for heat exchange process.

The following static equations describe the process

\[
\theta_{\text{eq,air\_out}}(t) = \lambda_{\text{fluid\_out}}(t) \cdot \theta_{\text{fluid\_in}}(t) + \lambda_{\text{air\_out}}(t) \cdot \theta_{\text{air\_in}}(t)
\]

where

\[
\lambda_{\text{fluid\_out}}(t) : \text{thermal convexity of (heating or cooling) fluid}
\]

\[
\lambda_{\text{air\_out}}(t) : \text{thermal convexity of the air}
\]

The factors \( \lambda_{\text{fluid\_out}}(t) \) and \( \lambda_{\text{air\_out}}(t) \) represent the effect of controlling fluid flow and the air flow on the resulting (equivalent) temperature. They both depend approximately linearly on the product of the corresponding mass flows multiplied by the corresponding heating coefficients. The sum of the both thermal convexities is 1, consequently

\[
\theta_{\text{eq,air\_out}}(t) = \lambda_{\text{fluid\_out}}(t) \cdot \theta_{\text{fluid\_in}}(t) + (1 - \lambda_{\text{fluid\_out}}(t)) \cdot \theta_{\text{air\_in}}(t)
\]

The linear dynamic process can be approximated by the first-order differential equation with unity gain

\[
T_{\text{HE}} \cdot \dot{\theta}_{\text{air\_out}}(t) + \theta_{\text{air\_out}}(t) = \theta_{\text{eq,air\_out}}(t)
\]

with

\[
T_{\text{HE}} : \text{time constant of the heat exchanger}
\]

The advantage of introducing the convexity factors is that they influence linearly the output (and the equivalent) temperature. The fluid convexity can be defined between zero and unity. In the knowledge of the temperatures the fluid convexity can be calculated from (8)

\[
\lambda_{\text{fluid\_out}}(t) = \frac{\theta_{\text{eq,air\_out}}(t) - \theta_{\text{air\_in}}(t)}{\theta_{\text{fluid\_out}}(t) - \theta_{\text{air\_in}}(t)}
\]

The fluid convexity is a function of the manipulated signal \( u_{\text{fluid}}(t) \) of the valve.

In (2) the thermal convexity was used. The aim of introducing the thermal convexity (Abdelghani-Idrissi et al., 2001) is to eliminate the nonlinear function between the real manipulated signal and the physical variable (mass flow multiplied by thermal capacity coefficients) from a thermal apparatus like the heat exchanger. In this way linear control algorithm can be used for the nonlinear plant.
The air mixing chamber and the room can be modelled in a similar way by using the thermal convexity (Kreutz et al., 2013).

5. PFC TEMPERATURE CONTROL AND SIMULATION

The temperature controller is a cascade one, consisting of
- outer loop (room) temperature controller
- inner loop (heater/cooler) temperature controller.

The dynamics of the room, the cooler and the heater are all modelled by a first-order lag. The following time constants were identified based on experiments: mixer: 0.5 min, both heater and cooler: 3.33 min, room (working hall): 23.33 min. The model was validated with real-time weather data over the year. The nonlinear static characteristic is represented by the convexity equations.

The PFC control algorithm is described in (Richalet and O’Donovan, 2009) and (Kreutz et. al., 2013) in details. The prediction horizon for the PFC was $n_p=1$ sampling step (common only for first-order processes) and the sample time was $\Delta t=100$ ms.

The PFC algorithm is simple for first-order processes

$$y_p(k) = -a_p y_p(k-1) + K_p (1 + a_p )u(k-1)$$

where $u$ the input, $y_p$ the process output and $k$ the discrete time (relative to the sampling time) is. $a_p$ and $K_p$ are the process parameters. The process model is approximated by

$$y_m(k) = -a_m y_m(k-1) + K_m (1 + a_m )u(k-1)$$

where the index “m” denotes the model contrary to the index “p” process. The manipulated signal is calculated for stepwise change $y_r$ of the reference signal by

$$u(k) = k_0[y_r(k) - y_p(k)] + k_1 y_m(k)$$

where

$$k_0 = \frac{1 - \lambda_r^{n_m}}{K_m [1 - (-a_m)^n_p]}; \quad k_1 = \frac{1}{K_m}$$

PFC assumes an exponential decrease of the future control error with reduction factor $\lambda_r$. PFC ensures for aperiodic processes a desired settling time of

$$t_{sys} = \left(3 \cdot \Delta t\right) / \ln(\lambda_r).$$

The following constraints were considered:
- The valves are constrained between 0% and 100 %.
- The convexity factor is related to the temperatures and the flows. The flow of the heat exchanger fluid is related to the valve characteristic, which is in the most cases a non-linear function. The convexity factor is back-calculated when the constraints were achieved.

As heater and cooler should never work simultaneously, a split-range control was realized. Fig. 7 shows the control structure.

The control algorithm was written in Matlab and was tested by a simulated process also written in Matlab.
The simulated PFC control in Fig 8 represents the control of the initial parameters controlling to a constant set-point of 21°C with a flap position of 100% fresh air. At beginning of this control the cooler works at limit and the controlled variable cannot be forced to the set-point. This is due to the fact that the fresh air temperature is very high on a hot summer day in August and the cooler is at constructional limit.

In Fig. 9 the floating temperature strategy is applied through the split into a heating set-point of 19°C and a cooling set-point of 25°C. The positive effect on the less activity of the valves results in the reduction of the deviation between the set-points and the fresh air temperature. The effect works stronger on the cooling performance while increasing the set-point from 21°C to 25°C and still with a reduction of the valve activity, but less stronger on the heating performance decreasing from 21°C to 19°C. The plot shows the floating of the temperature between the heating and the cooling set-points when no treatment by the heat exchangers is necessary. This cost-free modus depends mainly on the interactions between the fresh air temperature, the internal heat load and the due of fresh air.
6. IMPLEMENTATION OF THE CONTROL SOFTWARE

1. The program code was transferred to Simatic SCL (Structured Control Language) of Siemens AG. It was verified by a simulated process in a field PG (Programming Device). The PFC controller is a function block. Fig. 10 shows the main functions of the PFC controller block.

![Fig. 10. PFC function block in Simatic S7](image)

2. The control was on-line simulated in a test CPU and the data were recorded by a PLC analyzer and were transferred to an Excel data file. The structure of the control simulation is shown in Fig. 11.

![Fig. 11. Simulated process in the PLC](image)

The input variables were defined for test purposes via flags:
- MD4: weather data are passed through a flag,
- MD8: heater medium data are passed through a flag,
- MD12: cooler medium data are passed through a flag.

Fig. 12 shows the simulated control behavior to a stepwise set-point change.

![Fig. 12. Step response PFC S7](image)
7. INTEGRATING OF PFC TO PLC

The PFC functional block was integrated into the S7 project and linked to the necessary interfaces to switch between the PI(D) and the PFC control and to visualize the main parameters on the display. The process model quality was tested by calculating the model output compared with the measured temperature, see Fig. 13. (The main PFC controller contains the cascade and split-range loops.)

Fig. 13. Model check by temperature calculation

1. In the next step the calculated PFC controller output was compared with the manipulated signal of the PI(D) controller. If the PFC controller works well, then the two manipulated signals are near to each other (Fig. 14).

Fig.14. Check of the calculated manipulated signal

2. If both tests were absolved satisfactory then the control type can be switched from PI(D) to PFC. Because of the similar values of the both manipulated signals the switch will be bumpless (Fig. 15).

Fig. 15. Integration of PFC and PI(D) in the PLC

3. Fig. 16 shows the PFC controller parameters on the display. The adjustable parameters are:

- TAU: time constant,
- TRBF: closed loop settling time,
- AC/BC: transfer factor,
- R: delay,
- VE-Ventil-Stel: valve position.
Fig. 17 shows the selection of the controller type. The switch decided between the manipulated variables of the PFC and the PI(D), which generates the set-point for the control block of the heat exchanger (heater and cooler).

![Fig. 16. PFC control parameter for heater](image)

![Fig. 17. Selection of controller structure for heater](image)

8. REAL TIME CONTROL AND PERFORMANCE

After all steps of implementation and check were satisfactory, the control of the HVAC system was switched to PFC control. Fig. 18 and 19 shows the real-time control of PFC with an integrated floating set-point strategy. Fig. 17 shows the control at warm days in August and Fig. 18 at cold days in November.

![Fig. 18. Real-time control: PFC with floating set-point strategy in August](image)
For the conditioned zone it was possible to define the floating set-point range between a heating set-point of 19 °C and a cooling set-point of 25 °C coming also to the maximum tolerance limits. As shown in the control plots the control is very accurately on the set-point limits without any violation. Therefore the full range could be applied. The performance was evaluated by the fact that the sporadic real-time measurements match very well with the simulated control in section 5. Therefore the performance can be evaluated by the calculation of the cumulative actions of the heating and cooling with the equations (9) and (10)

\[
\text{Cumulative actions heating valve} = \sum_{k=1}^{N} u_{\text{HE_heating}}
\]

\[
\text{Cumulative actions cooling valve} = \sum_{k=1}^{N} u_{\text{HE_cooling}}
\]

where \( u_{\text{HE_heating}} \) and \( u_{\text{HE_cooling}} \) are the heating and cooling valve movements and \( N \) is the number of simulations.

Fig. 20 shows the relative savings when controlling on a floating set-point between 19 and 25 °C compared to a control on one set-point of 21 °C. For these calculations real weather data over a full year have been fed into the simulation program. The total benefit by reducing heating and cooling energy is here simulated with around 30%. Validated with real-time measurements calculating the energy consumption by means of the sensors placed on the heat exchangers (Section 2) a number of 25% for the specific HVAC system can be presented. This energy reduction is mainly achieved by the change of the set-point limits, to be sure that PFC control not to violate the maximum limits.
The cumulative actions of the heat exchanger valve, giving the mass flow of the heat exchanger fluid, are directly proportional to the absolute energy consumption

\[ W [\text{kJh}] \sim \dot{m}_{\text{fluid}} \sim \sum_{k=1}^{N} u_{4k} \]  

(11)

9. CONCLUSIONS

The implementation of a controller in an industrial PLC is critical because it can damage the process to be controlled. The different steps should be defined and validated with great caution.

The first step is to model the process, to simulate it and to validate the accuracy. The next step is to translate it in SCL and comply with the syntax and arrays of the controller. This SCL code has to be validated, through a separate model building block. Then the new control software can be transferred to the CPU. The next step is to validate the model: to check that the process temperature fits the model temperature. As both controllers, PI(D) and PFC, propose control signals an elementary comparison has to be performed between the two - possible different - values. If there is no major off-set, PFC can takes over the control form PI(D). Due to this cautious procedure a bumpless switch between the controllers can be realized.

Product engineers and operators do not like if a process is disturbed artificially. Therefore the success of the implementation of a new control algorithm depends on the skill of the commissioning. Future savings can be prevented by a not careful operation, e.g. by a bumped switch to a new controller or by violation of the technological limits. This paper reports on a successful implementation of a predictive controller, a subject which is very important but scarcely treated in scientific works.

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