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Performance analysis of a solar cooling system using self tuning fuzzy-PID control with TRNSYS

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Abstract

Considering the vision of covering as much as possible of global energy demand with high renewable energy fraction, our aim was to improve energy efficiency of a solar cooling system by innovative combination of optimized solar cooling, storage techniques and absorption chiller with highly developed techniques for control using known tools: TRNSYS and Matlab with Simulink. In this article we focus on the investigation of the accurate and robust control techniques which are flexible to all operating conditions of the system and in the same time improve energy efficiency and reliability. PID and fuzzy-PID methods are analyzed and compared by evaluating their performances on a solar cooling system, applied to an apartment house simulated with TRNSYS. PID is a traditional technique, considered accurate and simple; its main drawback occurs when applying it to transient system because of the linear characteristic and fixed parameters of controller. Therefore, a self – tuning procedure using fuzzy logic has been implemented to adapt the PID controller parameters according to state of the system. The control techniques evaluation and the system performance assessment have been done through TRNSYS and Matlab simulation. Here we present the methods of control used from the prospective of control sensitivity, quickness of reaction and complexity point of view. In the same time we will spot the influences on the performance of system when using the two control techniques. Later the model could be included in modules' library of TRNSYS.

Keywords: Control; PID; fuzzy logic; solar thermal energy

1. Introduction

Control theory is a highly developed field and together with energy efficiency and system reliability becomes a hot topic for researchers. Our purpose was to identify and tailor methods of control which would improve energy efficiency and reliability of HVACs, but also to keep good accuracy of control signal while eliminating the disturbances occurred in the system.

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Control systems theory begun to crystallize in late 19th century when Lyapunov laid the foundation of modern controllers using stability theory of dynamical models. PID controller was developed for automating steering system of ships, by another Russian researcher, Minorsky in 1922. Today PID control systems find application in all engineered system, and HVACs are *not* an exception.

The major limitations of PID control are caused by the fact that they are feedback controllers with constant parameters and no knowledge about the system. They are linear and symmetric, therefore their performance is varying in non-linear systems, as HVACs; especially, they have a delay in the response when system is changing behavior (e.g. when starting or changing from heating to cooling mode in a heating and cooling plant). The method which is mostly used to overcome this drawback is gain scheduling. This means finding more sets of parameters for more systems' states and choose the one which best suits the actual state. Defining more sets of parameters is time consuming. However the results presented in literature of PID controllers are showing that the response is precise if parameters are fixed properly. Starting from the concept that PID can be very efficient if an agile way of tuning the parameters is found, we thought that a robust way of classification of systems' states and a decision maker associated to it could be a good solution. Due to its qualities, robustness, non-linearity and disturbance inclusion fuzzy logic could be a suitable option to adjust parameters of PID controllers considering that HVAC control is a field where non-linearity and change of conditions or transients are usual and PID is quite inflexible to these characteristics.

In fact, in literature exists various attempts of combining these two methods, some of them were applied also to HVAC solar systems. A short description of the most important features of relevant publications attempting to combine the two methods for control of solar systems is provided further.

[1] developed membership functions for error and derivative of the error to determine k_p, k_i and k_d. They presented the use of traditional triangle membership functions but also a Gaussian membership function to compute the outputs. In [2] is explained a 2 level control. 1st level and the main one, is PID and second FLC (fuzzy logic control). PID parameters are defined by Ziegler-Nichols method and each member of the main control, P, I and D are affected by FLC output. FLC output takes into consideration error and derivative of the error. This method combination was applied to a solar air-conditioning system. [3] proposed an adaptive fuzzy sliding mode controller for a district heating heat exchanger. In reality they are presenting FLC using 2 temperatures as input and the required signal as output and compare with PID method. For them the simulations showed high control precision, stronger robustness and better rapidity. [4] are presenting a self tuning parameter using FLC for PID control applied to a fresh air system. In this case the controller uses error and derivative as input and Δk_p, Δk_i and Δk_d as output. The PID controller is adjusting k_p, k_i and k_d using the output. One case of using PID and FLC alternatively was found in [5] applied to a hybrid solar home system. They establish a rule for passing from one method of control to another according to deviation range accepted, on the principle that FLC it accepts a high deviation range while PID is more precise. [6] are presenting a fuzzy self-tuning PID cascade control of temperature of a solar heating system. They are using cascade algorithm in order to eliminate time delays caused by disturbances of controller. Basically the method is used in the same way of producing the k's parameters using error and derivative as fuzzy input as shown in literature above. After calculating PID value, they introduce one more control loop before signal exits the controller to influence PID output function to disturbances. One interesting approach is given by [7] to FLC and PID to control the temperature of a hybrid thermal energy storage system. They use FLC and feed forward method in order to determine the behavior of the room and implicitly, to determine the error to be used in PID controller of storage. By this means they make a predictive control including weather forecast and actual weather conditions. In [8] the authors present an FLC option for controlling the preheating of solar panel laminator. The benefit presented by authors is that it reduces the range of fuzzy self-adaptive PID controller, as in the preheating period there are most of transients occurring until one system stabilizes.

Concluding these articles review it was noticed that only two of them, [1] and [7], tested and validated on-line the methods on modeled systems. The implementation of fuzzy logic and PID controller to a real system is presented and discussed in [2] and [5] while the rest apply only simulated control to steady-state systems. As we noticed in this literature none of them used integral component to compute the PID parameters. Hence, we have seen the opportunity to evaluate this option for solar HVAC. The methodology of defining and applying the self tuning fuzzy-PID control to a solar cooling system will be exposed in this article. We used Matlab and Simulink tool to program the control and TRNSYS to simulate the system for one month (August). As TRNSYS doesn't contain a fuzzy-PID Type we attached the new control to transient model of the solar system using Matlab module. A comparison of accuracy of reaction and energetic performance is shown for PID and fuzzy-PID methods applied to the same system. Also the solar cooling system description is provided.

2. System Description

The system on which we simulated the 2 control methods is solar cooling applied to a 6 floors apartment house, using the weather data of Milano-Linate from TRNSYS database. The building was subject to refurbishment process, therefore prior to cooling system design we carried on an optimization process of building energy consumption and we achieved a peak cooling load demand of 33 kW.

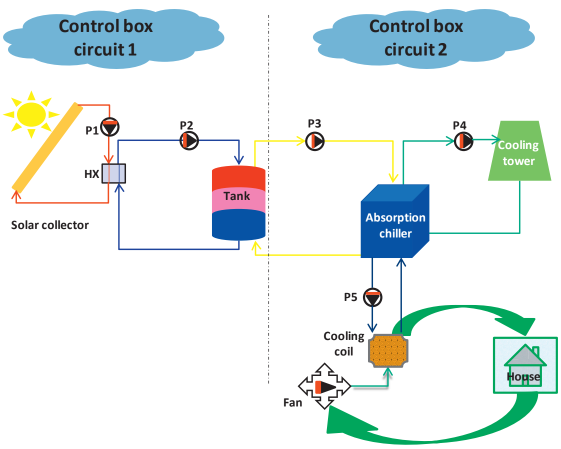

Figure 1. Solar cooling system scheme, modeled in TRNSYS

The solar cooling plant designed shown in Figure 1 is described in this section. As exhibited in the sketch main components of the cooling system are: the heating side or circuit 1: solar collector field, heat exchanger, thermal storage tank and 2 on/off pumps; cooling side or circuit 2: absorption chiller, cooling tower, fan-coil, 3 variable speed pumps and building.

During the optimization routine of the system's energy consumption we chased the improvement of solar fraction by reducing the amount of electrical energy consumption for the same cooling load covered. Solar fraction is the ratio of energy converted from Sun out of total energy converted by a system to provide the demand of the user as shown in equation (1). In this case the energy used from non solar sources is represented by the energy consumed by: pumps, fan, cooling tower and absorption chiller, as shown in equation (2). Minimization of energy consumption of these components means in fact increasing of solar fraction, and this was the target of optimization.

$$f = \frac{Q_{Sun}}{Q_{tot}} \tag{1}$$

SACS (Solar Absorption Cooling System) as an ensemble was designed using producer catalogue data. The influencing parameters of the major components are described below.

$$Q_{tot} = Q_{P1} + Q_{P2} + Q_{P3} + Q_{P4} + Q_{P5} + Q_{tower} + Q_{fan} + Q_{chiler} \tag{2}$$

Control Strategy of Simulated System

Using the specifications of [9] and [10] we design the control strategy of the SACS as it follows:

Circuit 1: P_1 and P_2 (single speed pumps) are controlled with the same controller signal – Control Box Circuit 1, as shown in Figure 1 and clarified below:

If $T_{col\_out} > T_{col\_in}$ with lower deadband of 2K and upper deadband of 4K, than P_1 and P_2 are ON until $T_{tank\_out} = 90$ °C. The deadband temperature difference was set up such that it can avoid the very often on/off cycling of pumps, which can cause damages and instabilities in temperature variations. T_{col_out} is the outlet temperature of the collector, T_{col_in} is the inlet temperature of the collector and T_{tank_out} is the hot side tank temperature outlet.

Circuit 2: P_3, P_4, P_5, fan and cooling tower are variable speed components and they are controlled for comparison reasons once with PID controller and in the second case with Fuzzy-PID controller, receiving in both cases the same signal for all the 5 actuators in the same time:

- PID controller is programmed in MATLAB and called by TRNSYS via Type155. Is able to provide variable signal between 0 and 1. The MATLAB engine is launched as a separate process and it behaves like a TRNSYS module. We chose MATLAB instead of using PID controller Type23 because of easier manipulation when we start to tune PID parameters. An iterative mode of this component is set, meaning that TRNSYS is calling MATLAB for the iterations of each time step only after convergence of iteration. The zone set temperature is compared with actual measured for each time step in Matlab. The signal sent to actuators is computed according to description of PID controller from following section.
- Fuzzy-PID is also able to provide a variable signal between 0 and 1. The PID part of the controller is identical to the one programmed previously and the fuzzy part is modeled using Simulink Toolbox as described in following section of the paper. Due to loop connection between TRNSYS-Matlab-Simulink the simulation is slower than PID. First TRNSYS is calling Matlab for the iteration of each time step, secondly Matlab is computing the error based on which Simulink to scales the parameters, and third, Matlab computes the signal and sends it back to system at every simulation time step.

3. Methods Used for Control

3.1. PID Controller

PID controller is a technique widely used for various controlled systems. Using the trial and error method for defining all 3 parameters of PID according to the block diagram of controller is time consuming. Therefore, here we used Ziegler–Nichols method [11], which is a heuristic method for defining the weighting parameters of PID controllers. In principle the method sets the I and D parameters to 0 and adjusts the P parameters until it reaches the value of ultimate gain, called K_u, at which the oscillations of the output are constant. K_u and oscillating period (T_u) are used to set I and D parameters according to Table 1.

Table 1. Ziegler–Nichols method using some overshooting [13]

Control Type	K_p	K_i	K_d
PID	$0.33K_u$=0.066	$2K_p / T_u$=0.0264	$K_pT_u / 3$=0.11

3.2. Fuzzy-PID Parameter Tuning Method

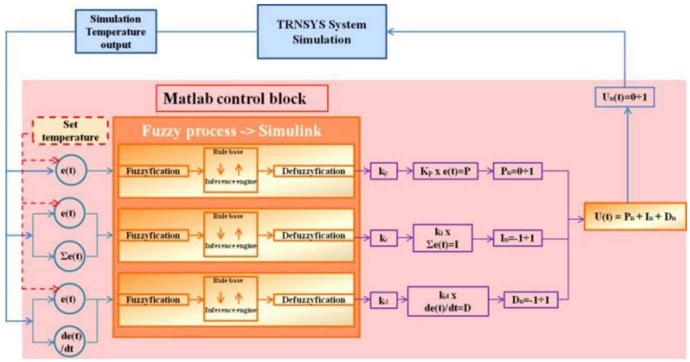

Figure 2.Signal exchange scheme between TRNSYS, Matlab and Simulink

The intention of this research is to use fuzzy logic – as described by: its inventor Lotfi Zadeh [13], Ross in [14] and many other authors – to tune PID parameters (k_p, k_i and k_d) in order to maximize solar fraction f and optimize energy consumption of the system. When designing the control method we took into account the logic of present error represented by proportional component, past error represented by integral and future error represented by derivative component of controller and the effects of increasing the parameters individually pointed out in [15].The algorithm of the fuzzy-PID controller is summarized in Figure 2 and described as it follows.

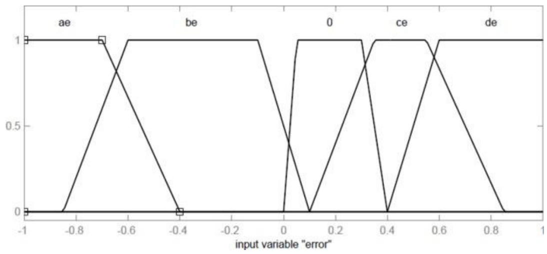

Figure 3. Membership function of error input

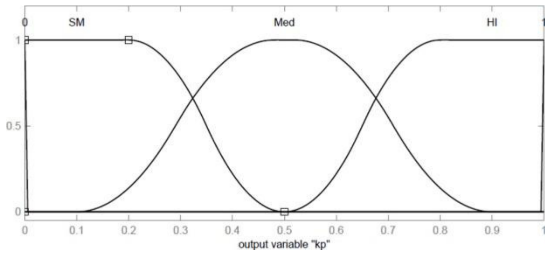

Figure 4. Membership function of proportional parameter output

- P component is calculated as: $k_p \times e(t)=P$. It is responsible for the actual error. In our study we gave this component the highest importance so we set the output k_p dependent only on one input, e(t). Considering the system cannot handle instantaneously very high errors we assumed the maximum $e(t)= T_{zone}-T_{desired} \leq |1|$.The universe of discourse is set to [-1,1] for input e(t) as shown in Figure 3 and to [0,1] for the output k_p as shown in Figure 4.

Table 2. Definition of rule matrix for error parameter

	Rule
ae	0
be	0
0	SM
ce	1+0.2 x HI+0.5 x MD
de	1

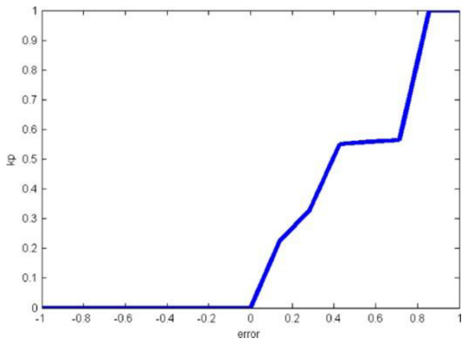

Figure 5. Plot of k_p output function to error input to FLC system

If e(t) will exceed its range, the extreme values from the range will be taken into consideration for both input and outputs. Figure 3 and Figure 4 show the division and shapes of membership functions for the input and output. The error universe of discourse is divided into 5 membership functions: ae and be are negative part, de and ce are positive parts and 0 is close to 0. For the output it was chosen the pi (π) shape in order to get smoother transition from one state to another. Both membership functions type, input (trapezoid and triangle) and output (pi shape) were available by default in Fuzzy Logic toolbox from Simulink.

The plot of k_p in Figure 5 shows the influence of input e(t) on output k_p. We defined crisp values for extreme conditions: 0 and 1, which emphasize the extreme conditions situations when necessary. The dependencies of the output (k_p) function to input (error) is based on rules defined in Table 2. When setting the rules shown we took into account the rules of parameters variation as described in [15].

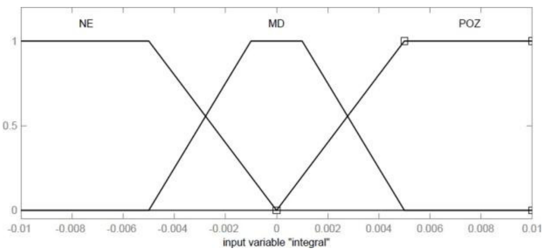

Figure 6.Membership function of integral of error input

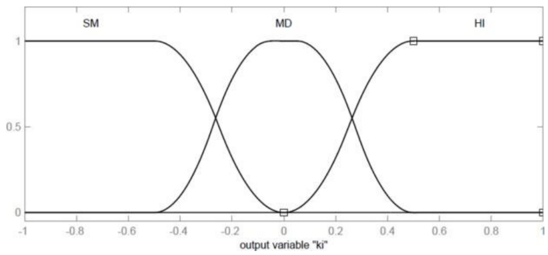

Figure 7. Membership function of integral of error parameter output

- I component is calculated by: $k_i \times \Sigma e(t) = I$. It is responsible for the past error. It influences the component P by decreasing or increasing it according to actual and past behavior (therefore the weight of this component is dependent on error and integral of error) in order eliminate the steady state error.

The integral of the error is always a problematic one, because of windup and overshooting danger. It is reasonable to think that this is the justification why in literature related to this type of controls applied to solar thermal systems it was not found the tuning of k_i based on integral of error as input. k_i is calculated usually using as input error, derivative of error or other variables like ambient temperature, weather data etc. It is difficult to establish the universe of discourse of integral due to its excessive change in time.

Therefore here we are proposing to use the integral as negative or positive rather than its real value.

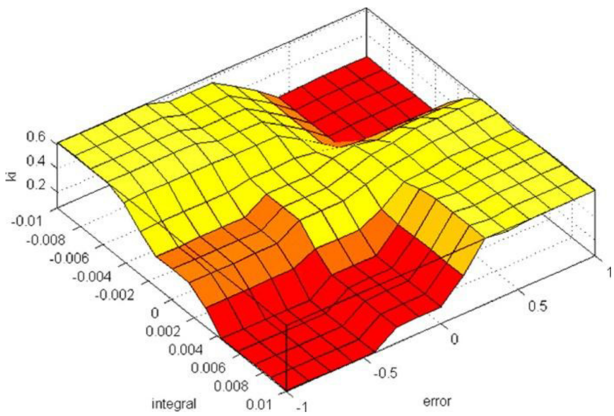

Figure 8.Surface plot of k_i output function to error and integral input to FLC system

Table 3. Definition of Rule matrix for integral parameter

	NE	POZ	MD
ae	HI	HI+0.5*MD +0.1*SM	HI+0.5*MD
be	HI	HI+0.5*MD	HI
0	HI	HI+0.4*MD	HI
ce	HI	0.8*HI	MD+HI
de	HI+ MD	0.8*HI	HI

The real value is scaled such that it will keep the sign of variable but it will be between the range [-0.01 0.01], as shown in Figure 6. For definition of integral universe of discourse and membership functions we had to make use of TRNSYS repeatedly simulations in order to define the weightening factors as shown in Table 3 and taking into account always the rules defined in [15] for effects of increasing and decreasing the parameters on reaction of the control signal. The universe of discourse of input *Σe(t)* is divided into 3 membership functions: negative (*NE*), positive (*POZ*) and medium (*MD*). The output membership functions are similar to the previous one, k_p. The universe of discourse of output is [-1,1] in order to emphasize that I is adjusting component P not setting up the signal as shown in Figure 7. The surface plot of the parameter determination according to rules defined in matrix from Table 3 for given outputs of scaled integral and error is given in Figure 8.

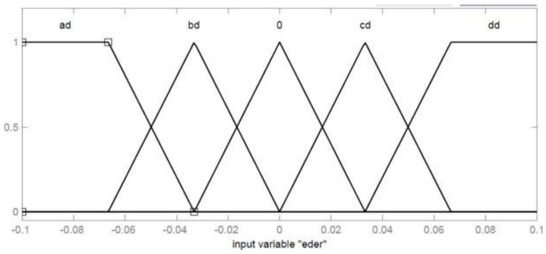

Figure 9. Membership function and universe of discourse of derivative of error (*de(t)/dt*) input

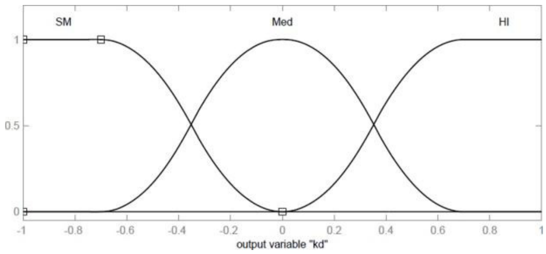

Figure 10. Membership function of derivative of error parameter (k_d) output

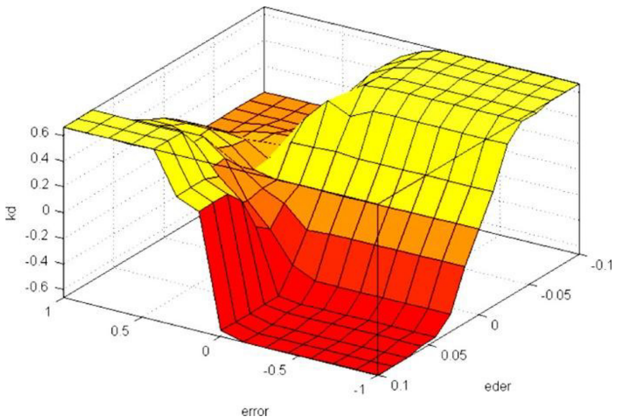

Figure 11.Surface plot of kd output function to error and derivative input to FLC system

- D component is calculated by: $k_d \times de(t)/dt = D$. When adjusting it we took into consideration present and future actions, therefore the weight of this component is dependent on error and derivative of the error. The derivative of the error normally should not have a wide range because temperature cannot vary too much from one time step to another, same as described for component P. Universe of discourse of derivative input is [-1 1] as shown in Figure 9 and of output k_d is [-1,1] as shown in Figure 10 and identical as for k_i for the same reasoning: D component in general should not give the trend of signal but should adjust component P by reducing the overshooting and settling time. The rule matrix defined as shown in Table 4 is reproduced in surface plot of k_d function to e(t) and de(t)/dt in Figure 11.

The increase weight of P is obtained first by setting dependencies of the 2 parameters I and D on themselves but also on P. Therefore k_i is depended of P and I and k_d is dependent on P and D, while P is dependent only on itself. Second, the weight of P is increased by setting the normalized two component I_n and D_n and k_i and k_d in the range of [-1,1], while normalized P_n and k_p in the range of [0,1].

Table 4. Definition of Rule matrix for derivative parameter

	ad	*bd*	*0*	*cd*	*dd*
ae	*HI*	*HI*	*MD*	*SM*	*SM*
be	*HI*	*HI*	*MD*	*SM*	*SM*
0	*HI*	*HI*	*MD*	*0.5MD+0.5SM*	*0.5HI+0.5MD*
ce	*MD*	*0.2HI+0.8MD*	*MD*	*0.5HI+0.5MD*	*HI*
de	*MD*	*MD*	*HI*	*HI*	*HI*

The inference engine chosen for obtaining all 3 components is Mamdani[16], because it shows the clearest representation of the outputs. We have chosen the most common defuzzification method, centroid as shown in equation (3).

$$C = \frac{\int \mu(V) \times V \, dV}{\int \mu(V) \, dV} \tag{3}$$

In order to obtain the final signal we sum normalized components to produce *U(t)*: $P_n + I_n + D_n = U(t)$.The normalized *U(t)*, as shown in Figure 2, is the final control signal.

4. Results and discussions on control techniques

The results are presented for desired set temperature of 24 °C for 1 cooled zone of the building (the column of 6 floors of smallest apartment). We simulated the system for 1 month, August, using a simulation time step set at 3 minutes. At a glance, looking at Figure 12, Figure 13 and Figure 14 fuzzy-PID control technique shows an improvement in performances. Figure 12 represents the zone temperature of the building while applying the PID and fuzzy-PID control and uncontrolled zone temperature. The maximum error shown by PID is 0.29 K and for fuzzy-PID 0.69 K, however the stability of temperature when using PID is lower than fuzzy-PID.

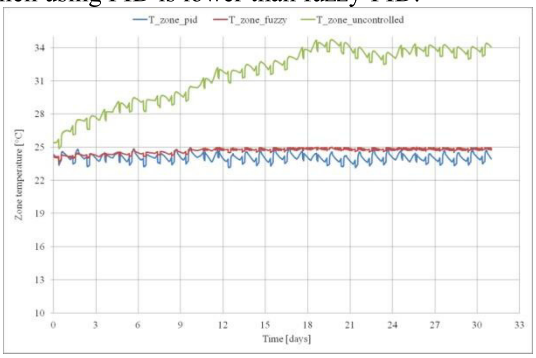

Figure 12. Zone temperature profile for 1 month simulation of PID, fuzzy-PID control and uncontrolled zone

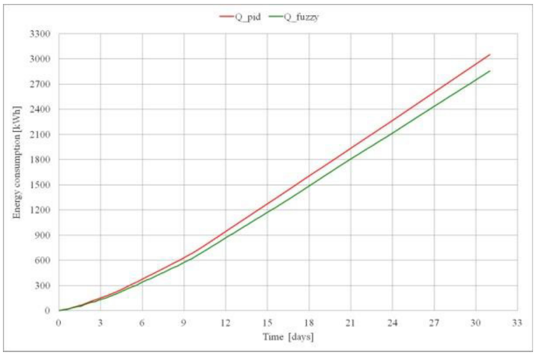

Figure 13. Electrical energy consumption during 1 month simulation of PID and fuzzy-PID control

Since we applied the two method of control only to 2nd circuit, in Figure 13 we represent the energy consumption for the full period of simulation of month of August for 2nd circuit only. The improvement when using fuzzy-PID compared with PID is of 6.3%. However the improvement for overall system is of 5.9%, due to unchanged 1st circuit control method but also increase of use of 1st circuit which in fact leads to increase of solar fraction from 38% when using PID to 42% when using fuzzy-PID.

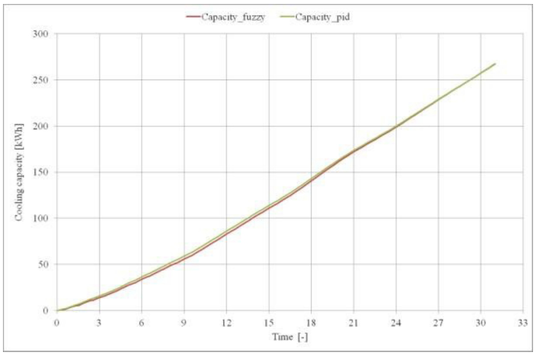

Figure 14.Cooling capacity provided to building during 1 month with PID and fuzzy-PID

The total cooling capacity of the system is similar for both control methods for the full operation period (Figure 14). This means that the same amount of energy is provided to the building when using PID and fuzzy-PID.

Fuzzy-PID shows better flexibility and quicker reaction, this being the reason why the temperature of the zone is more stable with this control method.

The solar fraction is increasing with 32.7% in the case of using fuzzy-PID compared to PID as controlling method. The summary of results for the month of August using both PID and fuzzy-PID control methods is given in Table 5.

Table 5.Summary of simulation results

Control type	Energy consumption of circuit 1 & 2	Energy consumption of circuit 2	Total Solar Fraction	Total Cooling capacity
	kWh	kWh	[-]	kWh
PID	3254.9	3048.8	38%	266.8
fuzzy-PID	3063.3	2856.6	42%	267.3
Comparison	5.9%	6.3%	3.5%	0.2%

5. Conclusions

In this work we presented a solar cooling system with absorption chiller designed for an apartment building and simulated in TRNSYS. The goal was to identify and tailor methods of control which would improve energy efficiency and stability of HVACs, but also to keep good accuracy of control signal while eliminating the disturbances occurred in the system. We attempted to improve the use of fuzzy-PID for HVAC systems and compared it to simple PID. The classical PID was presented as cornerstone for developing the fuzzy-PID and both were programmed in Matlab/Symulink to be simulated with TRNSYS model of the above mentioned system. TRNSYS is a good modulated HVAC system simulation tool and it has included modules for PID control. Here we used Matlab for PID because at the end it was easier to add fuzzy logic components to it, as the module for fuzzy-PID is not available in TRNSYS.

Taking into account the major assumptions made (3 minutes time step and 1 control signal for more actuators), the combination of fuzzy logic with PID to tune PID's parameters, showed more reliable than simple PID (with fixed parameters) because of:

- quicker reaction;
- higher output signal stability for the operating conditions;
- lower energy consumption for similar cooling capacity provided;
- higher solar fraction.

When used alone, PID can perform poorly in HVAC because the method is linear and symmetric. In some conditions it shows good control in other not so good. Here we have chosen the conditions for which PID reacts the best and shown results for the same conditions also for fuzzy-PID. Therefore it is needed to tune the parameters according to the state of the system. The advantages of fuzzy logic used for tuning the PID's parameters can overcome the disadvantages of PID control. Hence, the combination of the 2 methods is expected to show the same trend of improvement as presented above also in reality. The given methodology for defining fuzzy logic memberships and universes of discourses is general, so it can be used for controlling other similar HVAC systems.

The deliverables from this research are:

- dynamical simulation by combination of TRNSYS-Matlab-Simulink to analyze the behavior of the system when controlled by the three methods proposed;
- generalized strategy to adapt the PID's parameters according to state of the system using fuzzy logic to regulate the temperature in a building zone. It refers to the methodology of defining fuzzy logic memberships and universes of discourses for input and output of PID signal;
- inclusion of integral parameter as part of decision maker for the overall signal output.

These methods are thought to be an additional contribution to building automation system, if they would be included in the monitoring and control mechanisms. Regarding complexity, simulation time is much increased for fuzzy-PID compared to PID due to the several links used here: TRNSYS-Matlab-Simulink which slows down the simulation at each time step. In order to ease the simulation it would be nice to include fuzzy-PID as a TRNSYS Type and test it for more configurations of systems. It would be interesting to validate this method on real system.

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