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Short Review on HVAC Components, Mathematical Model of HVAC System and Different PID Controllers

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Abstract – *This paper is presented for short review of mathematical model of HVAC system as well as different tuning method of PID controllers such as try and error, PSO, robust time response, CHR, Ziegler Nichols and fuzzy logic controller to control the parameters of HVAC system via system identification toolbox. Decoupling algorithm via RGA method is used to convert the MIMO modified system to single SISO systems. The comparisons of different controllers to trace the target values are illustrated.* ***Copyright © 2014 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Modified Model, HVAC Components, RGA, PID Controller, PSO, Ziegler-Nichols, CHR, Robust Time Method, PSO, Fuzzy Logic*

I. Introduction

Nowadays, heating ventilation and air conditioners (HVAC) are commonly used in our lives, especially in the tropical and subtropical regions of the world. HVAC is an equipment that designed to adapt and adjust the humidity as well as temperature in places [1].

HVAC system is a combination of heating, cooling and ventilation system that controls the temperature, humidity and cleanliness of the air to improve the overall air quality inside a building. Typically, an HVAC system is used to offset the thermal load (Qz) and moisture load (Mz) in a thermal zone and to maintain desirable set-points for comfort condition parameters such as temperature, relative humidity (RH), CO2 content, and air velocity. Among the different parameters, temperature and RH have more direct influence on the performance of HVAC systems in nearly all applications [2]-[3]. Multivariable makes it extremely difficult to obtain an exact mathematical model to improve control quality [4]. Generally, HVAC systems must ensure the comfort of the occupants in a building. HVAC systems are recognized as the greatest energy consumers in commercial and institutional buildings. Generally, designers use common sense, historical data, and subjective experience in designing these systems [5].

The fuzzy logic (FL) ,artificial neural network ,and expert systems methods can be used to do the system identification in HVAC in order to estimate future plant outputs and obtain plant input/output sensitivity information, [6] proposed the functional link neural network to do the system identification in the HVAC system; This system represents a simplification of an overall building climate control problem, but retain distinguishing characteristics of an HVAC system. Beside methods above, there are many other ways to complement the system identification.

An online maximum-likelihood based identification algorithm is developed for the air conditioner system.

The experimental setup was designed to collect data in order to identify the system parameters. Finally the result of work shown that the estimated system was reliable for future study [7]. However, it is important to notice the complexity of an HVAC system with distributed parameters, interactions, and multivariable makes it extremely difficult to obtain an exact mathematical model to improve control quality [4].

HVAC control is the most important strategies in the building for saving energy. The importance of controlling of the HVAC system can be found that by increasing of 1% improvement in energy efficiency of these systems, save millions of dollars at the national level [8]. One of the most challenging problems in designing a good control system for the HVAC system is that of matching the dynamic characteristics of its process with those of the controller. In other words, a controller that will provide the desired closed loop performance can be designed if the dynamics of the process and the characteristics of the disturbances affecting it are known [9]. In recent years, there has been an increased interest in modeling the HVAC system and its components, using either theoretical or experimental approach. The paper is organized as follows: Section II summarized mathematical model of the HVAC system. Section III is explained the HVAC model and drawback of the system. Then in sections IV, V the different types of controller which are used to control the parameters of the HVAC system are described.

II. Mathematical model of HVAC system

In general, the mathematical model of HVAC systems is categorized into the following categories:

- Complete HVAC system models

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- Models of the different components in a HVAC system
- Models according to the heating and cooling zones

II.1. Complete HVAC System Models

Complete HVAC system model is one type of the models where the whole complete system is modelled as a, for example, a first order model with time delay [10]-[11]-[12] or bilinear model [13]-[14].

However, reducing the computational effort in the identification and controlling of HVAC system are two advantages of this type of model but, because of nonlinearity its application seems limited which requires more accurate model. The overall goal in bilinear model is to plan a feedback law that uses the temperatures $T_2(t)$ and $T_3(t)$ to modulate the two quantities, heat input and volumetric airflow.

In order to minimize a performance index which balances comfort level beside cost effective. [15] used single-zone variable air volume (VAV) HVAC&R system as a bilinear model to consider for describing both temperature and humidity dynamics. Unlike the work in [14] which defines the thermal space temperature and humidity as the outputs.

II.2 HVAC Component-Based Models

The design of efficient controllers for central ventilation and air conditioning HVAC systems are largely depends on the viability of good dynamic models of the system. It is important to developed analytical model for fundamental principles. The model would be useful for comparison, validation and more important for multivariable controller design using modern control theory [16].

In the HVAC component-based modeling, the different parts of the HVAC plant are modelled separately. The purpose is mainly to handle the control of each HVAC component individually. Several researchers have contributed to the development of HVAC component models. The followings are the most commonly modelled components of the HVAC system:

II.2.1. Duct

[17] extracted a dynamic models for a duct system.

The pipe or duct model is design to account for thermal losses to the surroundings, the thermal capacitance of the pipe or duct itself and the transport delay. It consist of three steps:

First, the steady state fluid outlet is calculated. Next, the dynamic consider from an Eulerian perspective i.e., following a fluid element down the conduit. Finally, assumes that the thermal losses to ambient condition occur at their steady state rate at all time. [18] mentioned that the duct model is intended to represent relatively large pieces, and has been used to model a 216 ft duct.
The accuracy of the model is difficult to quantify since it depends on number of factors including simulation time step.

II.2.2. Fan-Motor Model

The fan-motor model describes the relationship between fan speed, motor input power and fan pressure [18].

II.2.3. Heating Coil

The heating coil model uses a equation for effectiveness as a function of number of transfer unit (NTU) for across flow heat exchanger with both fluids unmixed [19]-[17]. It was shown that the steady stated result which is inaccurate and under some conditions thermodynamically impossible, due to simplified assumption that the mean air temperature exposed to the coil is the arithmetic average of the inlet and outlet temperature.

II.2.4. Cooing Coil

[20] modelled air flow in the duct system. The cooling water at θ_{ci} is supplied to the coiling coil and returns at a temperature of θ_{co} to the storage tank. [19] explained that most important component of every HVAC system is cooling coil.

The increased emphasis on variable operation of HVAC equipment warrants a greater understanding of the dynamic behavior of cooling coils.

II.2.5. Chiller and Storage Tank Model and Chilled Water Coil

[21] explained that the chilled water coil model was developed for two reasons the first was to use model to study the direct digital control system and the second was to investigated the dynamics coil for different operating conditions.

The model is able to predict the outlet air temperature of the coil as a function of the water flow rate. One of the inherent characteristics if chilled water coil is their nonlinear transient response. [22] made a non linear model of a coil by varying the time constant with the water flow rate. The described method is similar to the Pearson's method.

The coil model which is measured with the actual response of chilled water effectively predicted the response at different values of gains for each type of control algorithm.

II.2.6. Humidifier

[19] mentioned that measurement and control of moisture in the air is an important phase of air conditioning. [20] mentioned that the humidification is a requirement in some areas due to the very humidity that exist in cooling mode in winter.

The humidifier is the most interfaces between the air handling unit and the room. It was mentioned that the humidifier model is separated from the air handling unit.

It makes to successful implementation of an air handling unit.

II.3. Heating and Cooling Zones Models

Cooling and dehumidifying coil model is the most important interface between the primary plant (chiller) and secondary air disturbance system. Therefore, several cooling models are developed. Myers and his coworkers [23] modelled the transient response of cross flow heat exchangers evaporators and condensers. The dynamic of chilled water coil was modelled by [21]. [18] proposed the model of the cooling and dehumidifying coil.

The modification made was incorporating the effects of variable airflow rates in the coil, which occur in response to changes in fan speed. The model is capable of simulating different coil configurations by specifying parameters such as the number of rows, number of tubes and depth of coil. There are also other types of HVAC system modeling such as the model of two HVAC subsystems considered in series where [24] presented the modeling and control of an air conditioning system which was decomposed into two subsystems connected, in series with natural feedback. In addition, they obtained very good and satisfactory results in maintaining the room conditions close to the desired values.

III. System Description

The design of successful controllers for HVAC systems primarily depends on the availability of good dynamic models of the systems and mathematical equations that describe its behavior. The complexity of an HVAC system with distributed parameters, interactions, and multivariable makes it extremely difficult to obtain an exact mathematical model to improve control quality. In recent years, there has been a growing interest in the mathematical modeling of HVAC systems and its components.

Many researchers studied HVAC dynamic models using either theoretical or experimental approach. [17] derived dynamic models for a duct and a hot water coil. [25] developed an empirical nonlinear model of a hot-water-to-air heat exchanger loop that is used in developing nonlinear control law. [21] developed an empirical model of chilled water coil and used it to predict the system response to inputs with Proportional (P), Proportional Integral (PI), and Proportional Integral Derivative (PID) control algorithms.

The actual response of chilled water was measured to validate the coil model. They found that the coil model effectively predicted the response at different values of gains for each type of control algorithm. [26] described a procedure for deriving a dynamic model of an air-conditioned room by applying physical laws. [27] developed a room model to study the influence of the sensor position in building thermal control, since the temperature measured by the sensor of a room temperature controller depends on its position in the zone. They obtained a detailed list of criteria for the development of zone models.

[24] presented the modeling and control of an air conditioning system. The process was decomposed into two subsystems connected in series with natural feedback. They obtained very good and satisfactory results in maintaining the room conditions close to the desired values. Several authors studied the dynamic model response and transient response for space heating and cooling zones [28]-[29].

[30] used heat transfer and energy balance principles to create a linear model that represented a nonlinear cooling coil. [31] presented a transient HVAC system that included components such as a humidifier and mixing box, but no specific model for cooling or heating coils was given.

[32] offered a model for cooling coils with empirical parameters under the assumption that there would be a constant flow of air and water. [33]-[34] presented two cooling coil models that were complex and contained many iterative computations. [25] developed a nonlinear model for a heat exchange loop. [35] presented a cooling coil, mixing box and a fan for (VAV) system. Recently [19] presented a mathematical dynamic model for HVAC system components based on Matlab. Although this model is based on Matlab, it consists of nonlinearity, complexity and interconnection. The model of the HVAC system described by [19] is simplified and implemented by [36].

The system identification toolbox is used to model of the HVAC system and omit the difficulties of the original system. Temperature and RH controls, on individual basis, have counter effects on each other [37]-[38]. In a numerical study, [37] investigated the simultaneous and separate control of temperature and RH in a thermal zone. Moreover, in the simultaneous control, setting the controller parameters is difficult and, due to thermal coupling between RH and temperature, the response of the system is oscillating. As a result of that study, the coupling effects of RH and temperature should be considered, when it is desired to control such parameters simultaneously.

There are two approaches to address the decoupling of temperature and RH. First, the coupling behavior between temperature and RH can be overcome by utilizing a decoupling algorithm, when the control law is developed. For that purpose, control methodologies such as multivariable or intelligent control methods can be used. [39] designed a fuzzy controller to regulate the temperature and RH in a cold store by accounting for the coupling behavior of temperature and RH in the fuzzy controller actions. The rule-based control methodology solved the coupling problem of temperature and RH directly, and proposed fuzzy controller could control the system under disturbances and changes in setpoints efficiently.

To avoid interaction between temperature and moisture content responses, [40] conducted an experimental study, in which temperature and moisture content have been controlled simultaneously by varying the speeds of both compressor and supply fan in a direct expansion air conditioning system.

In that study, the controller is constructed by using the linearized model of the direct expansion air conditioning system and linear quadratic gaussian (LQG) method is used to design the controller. Although the used method in that study is straightforward for solving the problem, but when the setpoint of temperature in the thermal zone changes, moisture content of the thermal zone experiences some fluctuations and it nearly settles at setpoint after 3000 s.

In the second approach for decoupling, distinct channels for controlling the temperature and RH are developed in such a way that they are controlled individually through single input single output (SISO) channels and non-linear decoupling control algorithm can control temperature and RH individually [38]. In that study, the error between thermal zone temperature and the setpoint is input to a PD controller for determination of the control law that is used in conjunction with the same for RH by the decoupling algorithm for computing the final values of the controlled variables, namely, flow rate of air (fa) and flow rate of water (fw) in each time step. The controlled variables are then used to solve the differential equations for finding the thermal zone temperature and RH responses. One type of decoupling of the MIMO system is the method of relative gain array (RGA). This method is the most useful method to find the pairing of input/output which is one of the most significant methods used in the industry.

[41] mentioned that it is prefer to use the single SISO systems instead of using the MIMO system for better controlling of the system. [42] mentioned if a plant transfer matrix is diagonally dominant, it may be possible to design a good controller by considering each input-output pair as a separate loop. This approach is sometimes called decentralized control. Although, its flexibility choice is limited, but has several well-known advantages, such as tuning, sequencing of loop closing and the possibility to use the knowledge and intuition built around the control design of SISO systems.

In the decentralized diagonal architecture, a key issue is how inputs and outputs are paired [43]. This Issue has received a lot of concentration and attention over the last four decades. The most significant result is the original work of [44], who developed the idea of RGA. The RGA methodology is a widely used screening tool to help determining if a particular input/output pair (say, y_i and u_j) is a wise choice for implementing a SISO control loop, in the sense that coupling and interaction with other loops will be small, refining the Niederlinski result [45]. In the RGA, the channel interaction measure is built upon the d.c. gain of the MIMO process. In many complex and complicated industrial processes, the coupling among control loops often invalidates conventional single loop controllers. How to get decoupling control of such a system has become a topic of considerable importance in the field of control engineering [46]. Many researchers have tried to decouple of the system to make a better control of the MIMO system.

[47] designed a state feedback decoupling control system based on multiply variable system control theory to improve significantly the stability of the system. [48] proposed decentralized control systems, which are consist of independent SISO-controllers based on the diagonal elements of the system to control the MIMO system. The result yields higher close loop performance. [49] explained the main advantage of decoupling in two point control is that it provides the possibility of tuning and treating the multivariable system as two single composition loops; Moreover, Decoupling multivariable systems can have advantages such as an easier operating of a decoupled system than of an interacting one. Currently [36] used RGA method for decoupling of the HVAC system to convert the MIMO system in two different SISO systems. It is shown that the close loop of the decoupled HVAC system can fallow the target value very well rather than the original one.

IV. Control of the HVAC System PID's Tuning

This section explains the different methods of PID tuning such as Ziegler-Nichols, Chien-Hrones-Reswick (CHR), robust time method and particle swarm optimization (PSO) which are implemented to control simplified model of HVAC system [36]. The Ziegler–Nichols step response method is based on the idea of tuning controllers based on simple features of the step response [50]. Practically all books on process control have a chapter on tuning of PID controllers [51]-[52]. A large number of papers have also appeared, [53]-[54].

The Ziegler–Nichols rules for tuning PID controller have been very influential [55]. The rules do, however, have severe drawbacks, they use insufficient process information and the design criterion gives closed loop systems with poor robustness [56]. Ziegler and Nichols presented two methods, a step response method and a frequency response method. In this paper step response method is used for the close loop of HVAC system. The second control design method is the traditional CHR tuning for PI and PID controllers[57]. CHR is a modification of open loop Ziegler-Nichols method. They proposed to use "quickest response without overshoot" or "quickest response with 20% overshoot" as design criterion [58].

The CHR method emphasized the set-point regulation or disturbance rejection [59]. In addition one qualitative specification on the response speed and overshoot can be accommodated. Other type of tuning of PID controller is robust response time method which is tuned the PID gains to maximize bandwidth and optimize phase margin.

Because of the widespread use of PID controllers it is interesting to have simple but efficient methods for tuning the controller. Recently, tuning methods based on optimization approaches with the aim of ensuring good stability robustness have received attention in the literature [60]-[61]-[62].[63] used an optimal design of PID controller based on PSO approach for temperature control in HVAC.

PSO is an efficient search and optimization technique developed by [64]. The algorithm is based on a swarm of particles flying through the search space. In the concept of PSO, all individuals in the swarm have the same characteristics and behaviors, and each individual contains parameters for position and velocity. The position of each particle represents a potential solution to the optimization problem. The velocity is governed by a set of rules that control the dynamics of the swarm. In order to apply the PSO idea, matters such as representation of initial presentation of position and velocity strategies, fitness function identification and the limitation should first be considered [63].

[62] used PSO's method of PID tuning to control the temperature and humidity of the HVAC system. By comparing the amount of integral absolute error (IAE) of different controllers it is clear that the PSO method can be controlled much well than other tuning methods. Although, this method is suitable for tracking of the parameters but it consist of time consuming. Therefore another type of controlling which is more suitable for complicated case such as fuzzy logic controller is considered.

V. Fuzzy Logic Controller

Many applications of the fuzzy-logic have been studied in two decades. Almost any control system can be replaced with a fuzzy logic based control system. This may be overkill in many places however; it simplifies the design of many more complicated cases. So, fuzzy logic is not the answer to everything, it must be used when appropriate to provide better control [65]. Fuzzy systems are capable of approximating any real function on a compact fuzzy subset; such approximator have often been found superior to conventional modeling, especially when information being processed is inexact uncertain[66]-[67]. Main advantages of fuzzy logic in approximator, as compared to conventional approaches, is that no mathematical model is needed, and it is possible to use all available information about the process in the design of the fuzzy approximated scheme.

A fuzzy logic approximated converts a set of linguistic rules, based on expert knowledge, into an automatic approximation strategy. Employing fuzzy IF-THEN rules can model qualitative aspects of human knowledge and reasoning processes without employing precise quantitative analysis [68]-[69]. Status of fuzzy logic in 1998 is vastly different than that in 1978. Mathematical tools of fuzzy logic are established [70] and basic theory is in place.

Fuzzy logic based applications are ranging from consumer products and industrial systems to biomedicine, decision analysis and recognition technology's [71].

Fuzzy controllers can control nonlinear process model and time-delay process model significantly better than linear controller [72]. Fuzzy rule base (FRB) is the heart of fuzzy control system since all design parameters are used to assist and interpret these fuzzy rules and make them usable to design a fuzzy controller for a specific control problem [73]. Many researchers studied fuzzy controller to control the parameters of HVAC system. For cold store application of HVAC, [39] designed a fuzzy controller for temperature and RH in refrigeration system by considering their thermodynamic coupling. An attempt has also been made to replace the linear proportional control by maintaining interior environment of automobile [74].

Fuzzy controller is designed fuzzy control to control blower speed with dependency on engine coolant temperature and in-car set point. [75] investigated a new approach of fuzzy timing, Petri Net, for distributed temperature control to achieve optimum air temperature inside a car considering the comfort for each passenger, has also been developed; optimum HVAC control is applied to AC system for a car and fuzzy controller is used to independently control temperature at various locations inside a car. [76] employed a HVAC system controller with a control algorithm using fuzzy logic reasoning and rough set theory. In this case fuzzy logic reasoning has shown better performance in both temperature and RH control than rough set method. More over [77] worked on a nonlinear controller for VAV flow in HVAC system which is capable of maintaining comfort conditions within a thermal space with time-varying thermal loads acting upon the system.

[78] worked for the improvement of the refrigerant flow control method by using an electronic expansion valve (EEV) and employing the fuzzy self-tuning PID control method.

Experimental results show that the new control method can feed adequate refrigerant flow into the evaporator in various operations. [79] also worked on the control of EEV with fuzzy techniques using dynamic model of multi-evaporator air conditioners. [80] worked on fuzzy predictive control scheme based on a fuzzy model of a process and a discrete optimization technique (branch-and-bound), combined with an inverse model control law and applied this technique to an HVAC system consisting of a fan-coil unit installed in a test cell. Currently, [36] implements the fuzzy logic controller to control the parameters of simplified HVAC system. It is shown the controller can track the target values of the temperature and humidity very well.

The reason for using fuzzy logic in control applications stems from the idea of modeling uncertainties in the knowledge of a system's behavior through fuzzy sets and rules that are vaguely or ambiguously specified [81].

TABLE I
IAE OF DIFFERENT CONTROLLER

Controller	Tuning method	IEA's temperature of simplify/original	IEA's humidity of simplify/original
PID	Try and error	826.6/1257	29.9/31.83
PID	Robust time	849.2/761	84.2/242.8
PID	Ziegler-Nichols	1.69e004/1.49e+004	9.9/203.2
PID	C-H-R	1.20e004/1.5e+004	11.6/85.59
PID	------	1.71e004/1.20e004	135.5/127.6
PID	PSO	22.36/1.5e0023	10.42/1.5e0023
Fuzzy-logic	---------	357.8/3726	10.57/75.84

VI. Conclusion

In this study the mathematical models of HVAC system as well as advantages and disadvantages of them and different components of the HVAC system are explained. Because of the nonlinearity and complexity of the HVAC system it is considered to modify of full dynamic mathematic model of HVAC system. It is clear that the MIMO system has an interconnection with the parameters of HVAC system such as humidity and temperature. Therefore decoupling method is used. Different types of PID tuning as well as fuzzy logic controller are implemented on the simplified model of the HVAC system. The comparison of the simplified model and original shows that how much the simplified model can fallow the target values. Table I shows the amount of IAE for each controller which is used on simplified model of HVAC system and compare with the original.

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