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EFFICIENCY OF STATE-DEPENDENT PROPORTIONAL INTEGRAL PLUS OVER PROPORTIONAL INTEGRAL PLUS IN THE CONTROL AIR CONDITIONER WITH FREE COOLING

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Key words: *Integral of squared error (ISE), Integral of absolute control (IAC), Variance of input signal (VAR), Energy Efficiency (EE), State-Dependent Proportional Integral Plus (SDP PIP), Proportional Integral Plus (PIP)*

Abstract: *People have always wanted a conducive place with a controlled ventilation to create the needed atmosphere to live in. This article is based on the conditioning of the air with cooling systems and efficient control model and free cooling to make occupants of a closed room more comfortable. The article also focuses on performance optimization to preserve the components which make up the cooling system and also on energy efficiency by reducing the energy consumed by the cooling system. This study uses the Integral of squared error (ISE), Integral of absolute control (IAC), Variance of input signal (VAR) and Energy Efficiency (EE) performance criteria to compare the performance of State-Dependent Proportional Integral Plus to Bilinear Proportional Integral Plus (SDP PIP) control model to Linear Proportional Integral Plus (PIP) control model for efficiency in controlling the air conditioner and damper to allow ambient air at desired temperature into the room for free cooling, in order to reduce the energy expended in the control process to keep the room at the desired temperature. The performance criteria comparison is based on energy consumption minimization and the reduction of wear and tear of control components.*

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Introduction

Buildings use up about twenty to forty percent of the total energy expended in a controlled air-conditioned room. There is zero point five to five percent increase in the energy expended by buildings per annum in first world countries, therefore, small enhancement in the material and design of the building can greatly improve the energy saving of the air conditioning system and save expenses (Perez-Lombard L & C. 2008). Hence, knowledge in the discipline of mechanical and civil engineering can highly minimize the energy dissipated in closed buildings. However, most improvement of the design and materials used in a building is expensive. This article focuses on energy efficiency at little cost. Proportional Integral Derivative control system, is used in a lot of air-conditioning systems. Because of the uncertainties of the PID, it cannot always meet the expected control requirement (Hepworth SJ 1994). Bad control of temperature is one of the reasons occupants of a building are inconvenienced, because human beings have a normal body temperature of thirty-seven degree Celsius (37°C) which has to be kept relatively constant. PID control model is still used in practice, since it has not failed greatly (CP 1999). Many methods have been devised to deal with the uncertainty of a system. One of this method is by scheduling the gain of a PID controller, which adjust the parameters based on the dynamics of the system (Astrom KJ 1995). Temperature control of Heating, Ventilation and Air Conditioning (HVAC) systems has also been controlled in practice with fuzzy control and robust H-infinity control (So ATP 1994). The use of different methods in the HVAC industry is to accomplish robustness in the control system. In order to efficiently handle uncertainties in the dynamic of a system as a result of constraints, control techniques known as Proportional Integral Plus (PIP) Control and State-Dependent Proportional Integral Plus (SDP PIP) Control can be used. These Control systems can take advantage of the merits in the knowledge of building model and prediction of future constraints to control the system in a closed building more effectively to save energy. The control action also takes advantage of free cooling when ambient conditions are right and lets in fresh air from the ambient by a fan that controls air flow. This takes place when the ambient temperature is equal to the room temperature.

Literature Review

Ventilation Systems

Broadly speaking, air conditioning systems used in buildings, rely on the weather condition of the environment surrounding the building. By utilizing a system that mixes mechanical and natural ambient air, in countries where free cooling can be applied, can save over twenty percent of energy when compared to the use of only mechanical air conditioning system (El-Mankibi 2009). The concept of free cooling provides a comfortable closed room air conditioning at minimal cost, because it uses simple and cost-effective mechanism, which is the fan, to allow ambient air into the controlled room at desired temperature (El-Mankibi 2009). By separating the air conditioning system into an ambient air system that lets in ambient air and gives the desired cooling when it is the same as

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the desired temperature and an air conditioning system that provides the closed room temperature control (Oleksandr 2010).

Specialized ambient air ventilation system

Specialized ambient air ventilation system is a special unit used to control ambient air quality. The separated system mechanism, that is established on the separation of the ambient air ventilation and air conditioning of the air in the closed room. This brought about the specialized ambient air ventilation and closed room conditioning system with parallel sensitive cooling units. The air conditioning system combines both units to provide a cooling system to meet the required air condition in the closed building. The specialized air conditioning system is made up of dual systems; the initial system that takes away the latent load from the ambient air taken from the surrounding which is supplied to spaces with the aid of a hundred percent (100%) specialized ambient air system. While the other system takes away the space sensitive loads, with the aid of a parallel mechanical cooling system, like coil units consisting of fan, traditional air variable volume systems, and/or radiant cooling control boards for ceilings that functions separately, form the ambient air ventilation system (Jeong J.W. n.d.).

Specialized ambient air ventilation system can also be made up of one coil fan system which uses a dedicated cooling coil, dehumidification system and heat pipe for ambient air conditioning. The air conditioning system is made of a separate and dedicated secondary ambient air ventilation and thermic cooling which is dependent on control demand that applies radiant cooled ceilings for an air flow supply system. Ambient air is controlled by the specialized ambient air ventilation system to the needed off coil situation by a dehumidifying coil that is specialized for that purpose. A secondary coil of air conditioning units which are floor-based, uses the returned cooled water to take care of the building's effectual cooling load of the recycled air. The specialized air ventilation system brings down off coil cooling temperature which enhances the amount of humidity in the closed room. The intake ambient air is chilled by a heat recovery system to enhance the efficiency of the system. Specialized ambient air ventilation system is completely an ambient air constant volume system.

Personal Ventilation System

An option to the conventional air conditioning system is the personal ventilation system It is mainly a model patterned to give a local supply of air based ono individual ambient air needed (Sekhar 2007). Ventilation in the closed room can be enhanced, when equated to the conventional air conditioner via applying the desk or floor mounted air supply outlets. Research is still ongoing to optimize the personal ventilation in other to enhance the supply of ventilation, because its main goal is to vent fresh and clean air since it focuses on supplying clean fresh air without combining it with reused air (Oleksandr 2010).

Displacement Air Conditioning

Compared to the traditional air conditioner, a more enhanced air ventilation and energy efficient system can be gotten from the displacement air conditioner when the controlled closed environment is a tall building

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(Sekhar 2007), since a cool ceiling system in the climate region needs ceiling height of 10 ft to guarantee that indoor comfort and quality air condition in and enclosed and occupied controlled environment. But it is really expensive to design the displacement air conditioning system (Ghaddar 2008). Displacement ventilation is made up of discrete vertical temperature slopes and beaming asymmetry which serves as impediment in the simulation of a displacement ventilation system in a lot of simulation programs because their assumption is based on isothermal surfaces and properly-mixed air (Rees 2001).
A hydronic radiant chilling model which uses actively chilled surfaces to extract surplus heat and expel it from a closed room, can be attached to a constant volume ventilating system, producing a downsized air ventilation system, which gives dehumidification, because only ambient air is supplied for each person. A displacement ventilation system employs various hydronic systems to cool or heat up a conditioned room by radiant chilled ceiling space (Bahman 2009), floor cooling systems (Simmonds 2006), chilled beams (Walker 2007), wall convective panels (Kilkis 2006), or concrete core cooling (Olesen 2006). Efficient control of either ceiling temperature or Displacement Ventilation (DV) air supply condition or both of them
at the same time when using chilled ceiling and Dedicated Outdoor Air System (DOAS), can give quality indoor air, thermal comfort and energy efficiency (Mossolly 2008)

Methodology

System Modeling

Figure 1.1 depicts the HVAC plant setup, where DU, CCU and HCU represents dehumidifier unit, cooling coil unit and heating coil unit respectively. The T_{ai} represents temperature of air flowing into the room and m_a represents mass of air. T_{wi} and T_{wo} represents temperature of water supplied to the coil and temperature of water leaving the coil respectively. Mass of water is represented by m_w. The air handling unit condition the air based on the ambient air sensor and the temperature of the closed room with respect to the set point or desired temperature of the occupants in the room. The ambient air is let into the room by the system when it is at the desired temperature with the aid of fans.

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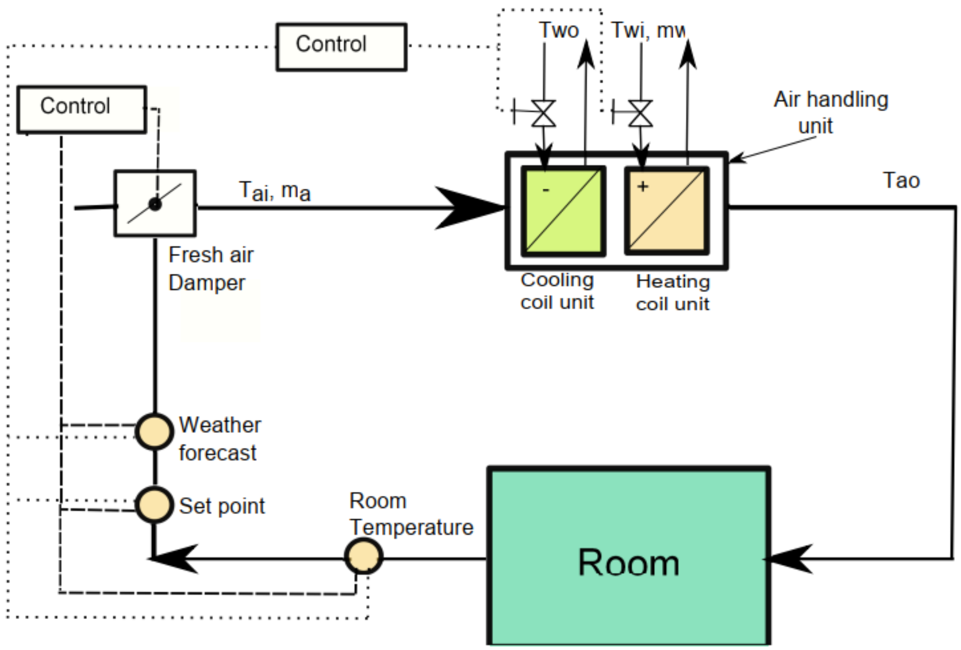

Figure 1.1 Schematic diagram of the Control of the Air Conditioner and Damper

Principle of operation of the Air Handling Unit(AHU)

The schematic diagram of the Air Handling Unit (AHU), the system has a damper which is used to stop or let in ambient air into the room when the temperature is right as shown in Figure 1.1, with a controller attached to the AHU which makes it active when the temperature of the ambient air is not equal to the desired temperature and a different controller opening the damper when the ambient temperature is equal to the desired and closing the damper when it is not equal to the desired temperature. The controllers consist of three sensors, the weather forecast sensor, set point sensor and room temperature sensor. When the AHU is active, the controllers take note of the set point with the aid of the set point sensor. If the ambient outdoor temperature and the room temperature are both greater than the set point, the AHU activates the cooling coil unit, to reduce the room temperature to the set point. The AHU stops cooling stops immediately the room temperature is reduced to the set point temperature. When the ambient temperature is equal to or less than the set point and the room temperature is greater than the set point, free cooling is used and the damper for fresh air is fully opened. However, the damper is closed if the ambient temperature becomes greater or less than the room temperature. But if the ambient temperature continues to drop significantly above the set point temperature, the AHU heating unit is turned on due to heat lost by the through the walls of the closed building to the ambient.

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Performance Criterion

The performance of State-Dependent Proportional Integral Plus (SDP-PIP) Control was compared with the Proportional Plus (PIP) Control of the air conditioner, based on the Integral of squared error (ISE), Integral of absolute control (IAC), Variance of input signal (VAR) and Energy efficiency (EE)

Integral of squared error (ISE)

The Integral of Squared Error (ISE) performance criterion is a measure of system performance formed by integrating the squares of the system error over a fixed interval of time, which measures the control effort expended in tracking the set point.

$$ISE = \frac{1}{M}\sum_{k=k_0}^{N}(y_k - r_k)^2 \qquad (1)$$

where M represents the number of data sample considered, N represents the discrete time of the simulation and discrete-time index k_0 equals 100 data samples. The square power term enables the ISE performance criterion to penalizes large control effort more heavily.

Integral of Absolute Control (IAC)

The Integral of Absolute Control (IAC) by assumption is proportional to the total control effort and determine the amount of control effort utilized by the control system. It is given by

$$IAC = \sum_{k=k_0}^{N}|u_k| \qquad (2)$$

Variance of Input Signal (VAR)

The Variance of input signal measures the accuracy of the control signal to accurately track the set point. The control signal has to accurately track the set point in order to protect the moving control components from wear and tear, such as the flow control valve. The equation is given by

$$VAR = \frac{1}{M}\sum_{k=k_0}^{N}(u_k - \bar{u})^2 \qquad (3)$$

where $\bar{u}$ represents mean value of signal u analyzed within a fixed time period N.

Energy Efficiency (EE)

Energy efficiency (EE) indicates the amount of energy used up by the system and hence, the energy efficiency of the system which is given by the equation

$$EE = \sum_{k=k_0}^{N}|Q| \qquad (4)$$

Where Q represents the rate of heat exchanged between the air flowing into the Air Handling Unit and the air flowing out of the Air Handling Unit and is given by $Q = mc\Delta T$. Where m is the mass of air, c is the specific heat capacity of air and ΔT represents the change in temperature.

Proportional Integral Plus (PIP) control

The PIP controller is a type of controller that depends on a state variable feedback (SVF) pole placement or pole assignment for all linear discrete time dynamic system that is controllable. The model of the PIP control uses the non-minimal state space algorithm whose state variable is defined in terms of the present and past values of the system output, the past input values, and also the integral-of-error which integrates the error between the output and the set point thereby bringing about adequate plant performance. (Young, Behzadi, Wang & Chotai 1987). In terms of block diagram, the PIP

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controller is an extension of the proportional-integral (PI) control, with enhancement of the PI action by higher order feedback and forward path compensator or digital filters.

Derivative and design of control law

The transfer function of a discretized system is given by

$$G(z) = \frac{Q(z)}{P(z)} \quad (5)$$

where Q(z) and P(z) are polynomials given by

$$Q(z) = q_0 + q_1 z^{-1} + ... + q_r z^{-r} \quad (6)$$

$$P(z) = 1 + p_1 z^{-1} + ... + p_e z^{-e} \quad (6)$$

The following definition of discrete time single input single output (SISO) transfer function is considered by (Young et al. 1987)

$$y_k = \frac{B(z)}{A(z)} u_k \quad (7)$$

where B(z) and A(z) are polynomials given by

$$B(z) = b_1 z^{-1} + b_2 z^{-2} + ... + b_q z^{-q} \quad (8)$$

$$A(z) = 1 + a_1 z^{-1} + a_2 z^{-2} + ... + a_p z^{-p} \quad (9)$$

in which z^{-1} denotes backward shift operator, defined as

$$z^{-1} x_k = x_{k-1} \quad (10)$$

Hence, the transfer function of a second order discretized system represented in block diagram form in Figure 1.2 is given by

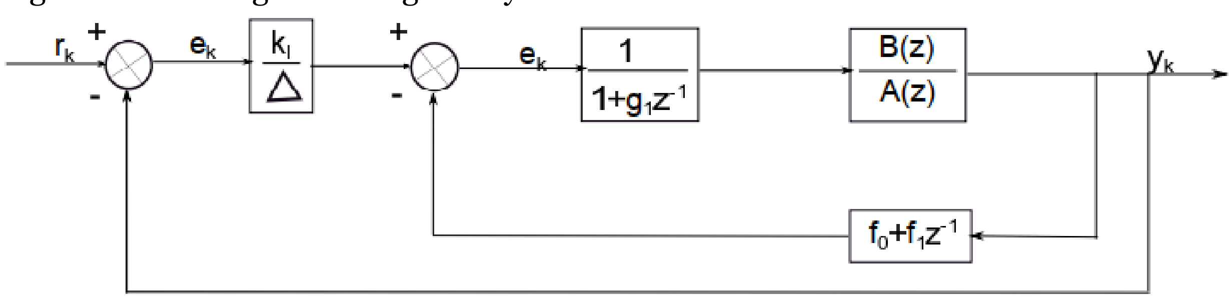

Figure 1.2: Schematic diagram of the controlled system

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$$\frac{y_k}{u_k} = \frac{b_1 z^{-1} + \cdots + b_q z^{-q}}{1 + a_1 z^{-1} + \cdots + a_p z^{-p}} \quad (11)$$

expressing equation (11) in difference equation form

$$y_k = -a_1 y_{k-1} - \cdots - a_p y_{k-p} + b_1 u_{k-1} + \cdot + b \quad (12)$$

one step ahead shift of the system output gives

$$y_{k+1} = -a_1 y_k - \cdots - a_p y_{k-p+1} + b_1 u_k + \cdots + b_q u \quad (13)$$

taking the y terms to the left-hand side of equation (13) and factorizing gives

$$y_{k+1} + a_1 y_k + \cdots + a_p y_{k-p+1} = [b_1 + \cdots + b_q z^{-q+1}] \quad (14)$$

applying the state variable feedback control law

$$u_k = -k^T x_k \quad (15)$$

where u_k denotes control action (input to our system), k denotes vector of control gain and x_k denotes vector of system states. The state vector is defined as

$$x_k = [y_k \quad y_{k-1} \ldots y_{k-p+1} \quad u_{k-1} \quad u_{k-2} \ldots u_{k-q+1} \quad (16)$$

in which z_k is the integral of error state given by

$$z_k = z_{k-1} + [r_k - y_k] \quad (17)$$

$$z_k - z_{k-1} = r_k - y_k \quad (18)$$

$$\Delta z_k = r_k - y_k \quad (19)$$

$$where\ \Delta z_k = 1 - z^{-1} \quad (20)$$

$$z_k = \frac{r_k - y_k}{\Delta} \quad (21)$$

the control gain vector, k^T is given by

$$k^T = [f_0 \quad f_1 \cdots f_{p-1} \quad g_1 \cdots g_{q-1} \ - k_I] \quad (22)$$

where k_I denotes the integral gain. Substituting equation (16) and (22) in equation (15) gives

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$$u_k = -\begin{bmatrix} f_0 & f_1 \cdots f_{p-1} & g_1 \cdots g_{q-1} & -k_I \end{bmatrix} \begin{bmatrix} y_k \\ y_{k-1} \\ \cdots \\ y_{k-p+1} \\ u_{k-1} \\ \cdots \\ u_{k-q+1} \\ z_k \end{bmatrix} \quad (23)$$

By matrix multiplication and representing Z_k as the expression in equation (21)

$$u_k = -f_0 y_k - f_1 y_{k-1} - \cdots - f_{p-1} y_{k-p+1} - g_1 u_{k-1} - \cdots - g_{q-1} u_{k-q+1} + k_i \frac{(r_k - y_k)}{\Delta} \quad (24$$

substituting equation (2.18) in equation (24)

$$u_k \left[1 + g_1 z^1 + \cdots + g_{q-1} z^{-q+1}]\right] = -f_0 y_k - f_1 y_{k-1} - \cdots - f_{p-1} y_{k-p+1} + k_I \frac{(r_k - y_k)}{1 - z^{-1}} \quad (25)$$

multiplying through by 1 - z^{-1} and making u_k the subject of the formula

$$u_k = \frac{-f_0 y_k - f_1 y_k z^{-1} - \cdots - f_{p-1} y_k z^{-p+1} f_0 y_k z^{-1} + f_1 y_k z^{-2} + \cdots + f_{p-1} y_k z^{-p+1} + k_I r_k - k_I y_k}{[1 + g_1 z^1 + \cdots + g_{q-1} z^{-q+1}]} \quad (26)$$

substituting equation (2.23) for u_k in equation (14)

$$y_{k+1} + a_1 y_k + a_p y_{k-p+1} = [b_1 + \cdots + b_q z^{-q+1}] \times$$

$$\frac{[-f_0 y_k - f_1 y_k z^{-1} - \cdots - f_{p-1} y_{k-p+1} + f_0 y_k z^1 + f_1 y_k z^2 + \cdots + f_{p-1} y_k z^{-p+1} + k_I r_k - k_I y_k]}{1 + g_1 z^1 + \cdots + g_{q-1} z^{-q+1} - z^1 - g_1 z^2 - \cdots - g_{q-1} z^{-q+1}} \quad (27)$$

multiplying equation (2.24) by

$$1 + g_1 z^1 + \cdots + g_{q-1} z^{-q+1} - z^1 - g_1 z^2 - \cdots - g_{q-1} z^{-q+1}$$

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and making $\frac{y_k}{r_k}$ the subject of the expression, the equation becomes

$$\frac{y_k}{r_k} = \frac{b_1 k_I + \cdots + b_q k_I z^{-q+1}}{XE} \tag{28}$$

where X_E denotes the characteristics equation given by

$$X_E = 1 + (a_1 - 1 + g_1 + b_1 f_0 + b_1 k_I) z^{-1}$$
$$+ (a_2 - a_1 + a_1 g_1 - g_1 + g_2 - b_2 f_0 + b_1 f_0 - b_1 f_1 - b_2 k_I) z^{-2} \tag{29}$$

representing the characteristic equation as the closed loop characteristic polynomial D(z) gives

$$D(z) = 1 + d_1 z^{-1} + d_2 z^{-2} + \cdots + d_n z^{-n} \tag{30}$$

comparing equation (29) to (30)

$$\begin{aligned} z^0 &: \quad 1 = 1 \\ z^{-1} &: \quad a_1 - 1 + g_1 + b_1 f_0 + b_1 k_I = d_1 \\ z^{-2} &: \quad a_2 - a_1 + a_1 g_1 - g_1 + g_2 - b_2 f_0 + b_1 f_0 - b_1 f_1 - b_2 k_I = d_2 \\ &\quad \vdots \end{aligned} \tag{31}$$

rewriting in matrix form

$$\begin{bmatrix} b_1 & 0 & 1 & 0 & \cdots & 0 & b_1 \\ b_2 - b_1 & b_1 & a_1 - 1 & 1 & \cdots & 0 & b_2 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ b_q - b_{q-1} & b_{q-1} - b_{q-2} & a_p - a_{p-1} & a_{p-1} - a_{p-2} & \cdots & 1 & b_q \\ -b_q & b_q - b_{q-1} & -a_p & a_p - a_{p-1} & \cdots & a_1 - 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & -a_p & 0 \end{bmatrix} \begin{bmatrix} f_0 \\ f_1 \\ \vdots \\ g_1 \\ g_2 \\ \vdots \\ k_I \end{bmatrix}$$

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$$\begin{bmatrix} d_1 - a_1 + 1 \\ d_2 - a_2 + a_1 \\ \vdots \\ d_n - a_q + a_{q-1} \\ d_{n+1} - a_{q+1} + a_q \\ \vdots \\ d_{n+1+m} - a_{q+1+m} + a_{q+m} \end{bmatrix} \quad (32)$$

State-dependent PIP (SDP-PIP) controller

Pole assignment control of non-linear dynamic systems described by state-dependent parameter (SDP) models is modelled using a quasi-linear structure in which the parameters vary as functions of state variable. The linear-like affine structure of SDP models allows for them to be considered at each sampling instant as frozen, linear instances of the nonlinear system, making the model more robust. This formulation is then used to design a PIP control law using pole assignment, this yields SDP control systems in which the state feedback gains are state dependent. Hence, the gains in the State dependent parameter are constantly being updated at every sampling instance based on the system state. (Taylor, Chotai & Young 2009)

The SDP model is given by the deterministic form as (Young 2000)

$$y_k = w_k^T p_k \quad (3.1)$$

where w_k^T is a vector of delayed input and output variables and p_k is a vector of SDP parameters,

$$w_k^T = [-y_{k-1} \dots - y_{k-1} u_{k-1} \dots u_{k-m}] \quad (3.2)$$

$$p_k = [a_1(x_k) \dots a_n(x_k) b_1(x_k) \dots b_m(x_k)] \quad (3.3)$$

where y_k represents the output and u_k the control input, while a_i (i=1,2,…n) and b_j (j=1,…m) are SDPs. The control input is assumed to be a function of a non-minimal state vector $x_k^T = [w_k^T U_k^T]$ in which $U_k = U_{1,k}, U_{2,k}, \dots, U_{r,k}$ is a vector of other available variables, not necessarily derived from y_k or u_k. Any pure time delay is represented by setting the leading $b_1(x_k) \dots b_{\tau-1}(x_k)$ terms to zero. n and m are

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integers representing the maximum lag associated with the output and input variables, respectively.

Consider the bilinear system represented by the following continuous time nonlinear differential equation

$$\frac{dy_t}{dt} = -\alpha y_t + \beta u_t + \eta y_t u_t$$

where subscript t denotes time and the model parameters α, β and η respectively denotes output parameter, input parameter and nonlinearity constant. For the control and simulation purpose, the above nonlinear differential equation is discretized using the structure

preserving Forward Euler discretization method, i.e $\frac{d}{dt} = \frac{(z-1)}{h}$, leading to

$$y_k = -ay_{k-1} + bu_{k-1} + cy_{k-1}u_{k-1}$$

where a, b and c respectively represent the output parameter, input parameter and nonlinearity constant. From state dependent model interpretation Equation (3.5) can be written as

$$y_k = -ay_{k-1} + (b + cy_{k-1})u_{k-1}$$

let $\tilde{b}_k = b + cy_{k-1}$, hence,

$$y_k = -ay_{k-1} + \tilde{b}_k u_{k-1}$$

Hence, from control law,

$$u_k = -\begin{bmatrix} f_0 & -k_I \end{bmatrix} \begin{bmatrix} y_k \\ Z_k \end{bmatrix} \quad (3.8)$$

$$u_k = -f_0 y_k + \frac{k_I}{\Delta}(r_k - y_k) \quad (3.9)$$

(3.4)

Shifting one step ahead and doing the necessary substitutions, the closed loop characteristic equations, $D(z^{-1})$ becomes

$$D(z^{-1}) = 1 + d_1 z^{-1} + d_2 z^{-2} \quad (3.10)$$

$$= z + d_1 + d_2 z^{-1} \quad (3.11)$$

hence, the matrix for pole assignment is given by

$$\begin{bmatrix} \tilde{b}_{k+1} & \tilde{b}_{k+1} \\ -\tilde{b}_{k+1} & 0 \end{bmatrix} \begin{bmatrix} f_0 \\ k_I \end{bmatrix} = \begin{bmatrix} d_1 - a + 1 \\ d_2 \end{bmatrix} \quad (3.12)$$

Thus, the control gains are explicitly written as functions of the SDPs and design coefficients. Since these parameters depends on the various functions of the input and output variables, the control gains themselves can also be expressed as functions of the input and output variables, as shown by Equations (3.11) and (3.12).

(3.5)

$$f0 = \frac{a + d_2}{\tilde{b}_{k+1}} = -\frac{a + d_2}{b + cy_k} \quad (3.13)$$

(3.6)

$$kI = \frac{1 + d_1 + d_2}{\tilde{b}_{k+1}} = \frac{1 + d_1 + d_2}{b + cy_k} \quad (3.14)$$

(3.7)

Comparison of PIP and SDP PIP

Linear PIP and SDP PIP have been considered and it was observed that the linear PIP was unable to effectively cope with changes in the

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sampling instances of set point and was also not able to cope very well with the parameters that were relatively constant at each sampling instance. Although linear SDP PIP is more complex compared to fixed gain linear PIP due to complexity in choosing the right state, it was able to linearize the system at each sampling instance, and it gave the optimal result.
Table 3.3 depicts the performance of Linear PIP and SDP PIP, based on set point tracking (ISE), control effort (IAC), wear and tear of moving control components (VAR) and amount of energy consumed (EE). With the closed loop poles of the Linear PIP placed at 0.8 and that of the SDP PIP placed at 0.96.

	ISE	IAC	VAR	EE
PIP	1.3994	17571.9061	6.1423	254324466.216
SDP PIP	11.3504	12337.8246	1.1885	254932857.4953

Table 1

From Table 1, it can be observed that in order to improve set point tracking (ISE) of the Linear PIP controller compared to SDP PIP, greater control effort was utilized (IAC), which causes greater wear and tear of control components (VAR), since they are more frequently adjusted to keep up with the set point. Greater amount of energy is consumed (EE) in the SDP PIP because of poor set point tracking when compared to the PIP control.

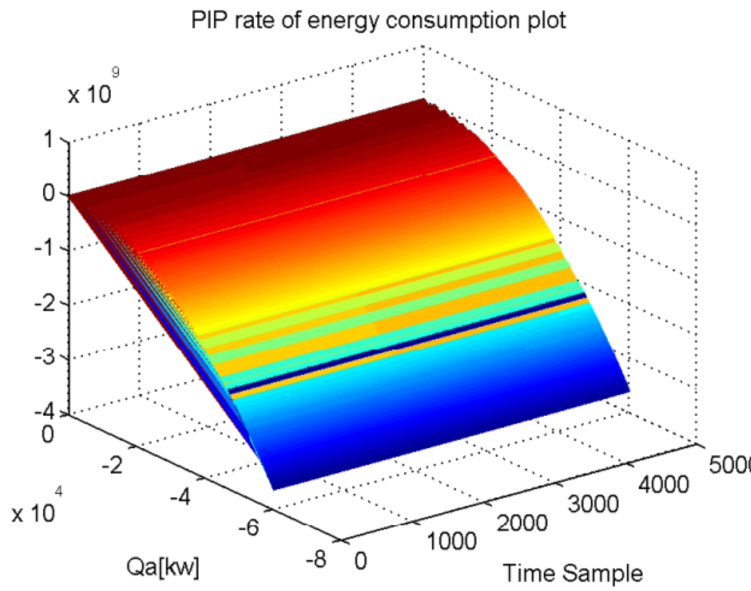

Figure 1.3

Figure 1.3 and Figure 1.4 depicts three dimensional plots of the rate of energy consumption by the PIP control and SDP PIP control respectively.

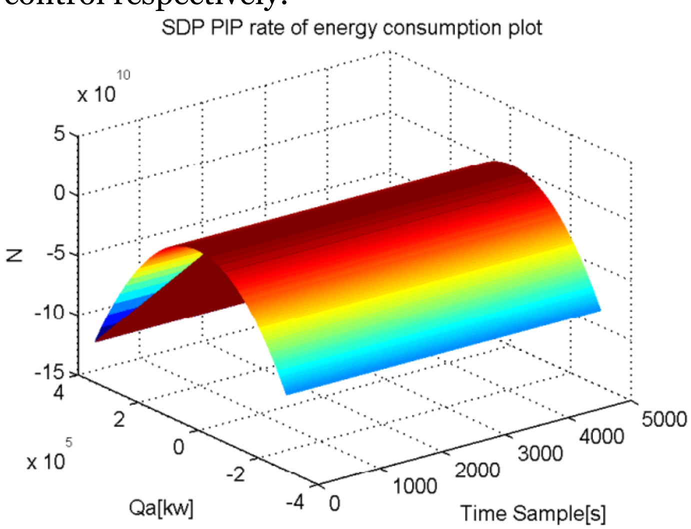

Figure 1.4

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From the plots, it can be observed that the volume of the SDP PIP control is more than that of the PIP control. Hence the rate of energy consumption of the SDP PIP control is greater than that of the PIP control

Conclusion

Linear PIP and SDP PIP have been compared in the control of an air conditioner with free cooling, based on control effort, energy efficiency, wear and tear of moving control components involved to keep the closed room within the desired temperature (set point tracking). It was observed that the linear PIP is more energy efficient than the SDP PIP at the expense of greater wear and tear of moving control components and greater control effort. The SDP PIP utilized lesser control effort but consumed more energy.

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