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Energy Conservation of Heat, Ventilation & Air-Conditioning System with the help of Fuzzy Controller

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Abstract: The Management and Automation of a Commercial building Heating, Ventilation and Air Conditioning (H.V.A.C) System has got enormous benefits from the use of all the available information sources. The modern H.V.A.C using direct digital control methods have provided useful performance data from the building occupants. The untapped data can be cultivated with the help of modern maintenance management databases. This research work has got the integration and application of these fundamental sources of information, using some modern and novel techniques. The cost and scalability of these techniques can be positively influenced by the recent technological advancement in computing power, sensors and databases. The important theme of this research paper is to increase the computational efficiency and practical usefulness of techniques, via some clever approximations.

Index Terms— Direct Digital Control (D.D.C.) , Energy Conservation, Fuzzy Controller, H.V.A.C., PID Controller

1 INTRODUCTION

ENERGY savings and thermal comfort are important for both facility managers and occupants.

As a result, they are open to new and innovative ways to improve or even replace currently existing practical methods that might not keep pace with the most recent advancement in the technology. In the large commercial buildings modern Direct Digital Control (D.D.C.) systems are becoming more favorable with the use of new sophisticated hardware. The H.V.A.C System components are used together and monitored remotely from a central location positions. The general trend in the design and commissioning of new commercial buildings includes the new types of these systems.

However, larger contingent of older buildings are existed that still use pneumatic H.V.A.C systems. Many facility managers are assigned with the operation of hybrid mix of older pneumatic building controls and modern D.D.C. There are also certain nuances that need to be handled properly, such as the geographical climate, weather, seasonal patterns' influence on the management of H.V.A.C system operation, perimeter vs. core zones, as well as building occupancy trends due to varied shifts and operating schedules.

Due to the deregulation of energy markets both domestically and abroad, the cost of energy and pricing/rate structures is another variable within the vast array of issues in a complicated operation that all building managers and their technicians must contend with. There are several different business processes as well as physical operating systems that existed in facility management which are often mapped onto supervisory management information systems. Hence there is often a repository of stove-piped information sources that are not necessarily linked and more often used on an ad- hoc/heuristic basis. As a result, the opportunity for widespread potential cost savings has been lost due to lack of knowledge or research concerning the intelligent use of these information-rich sources. The most recent technological advancement in computing has taken advantage to achieve the desired objectives of reduced energy usage and improved building occupant thermal comfort.

2 PROBLEM FORMULATION

The purpose of this research work is to provide an alternative to conventional PID (Proportional-Integral-Derivative) control modules embedded in large D.D.C panels. This research paper has focused on designing a "Rule Based Expert System" that combines fuzzy logic techniques with the engineering software, MATLAB. The conventional methods of improving chiller plant efficiency tend to focus on increasing the peak efficiency of individual components. Primarily, because the energy performance of constant speed chillers pumps and towers is maximized when components are operated as close to full load as possible. These methods generally involve the sizing and

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sequencing of plant equipment to fit a variety of load conditions, while minimizing the amount of online equipment. Simple D.D.C algorithms has been able to coordinate the operation of chillers, pumps and tower fans based on demand for cooling, which is determined by cooling coil valve position, chilled water temperature and tower leaving water temperature float within preset limits. These allow components to operate at their highest efficiency at all times. The demand based control sequences, which replaced PID control has been able to coordinate the operation of the condenser pumps and tower fans based on chiller power (kilowatts). Demand based control is an effective means of operating an ultra efficient all variable speed chilled water plant.

This research work focuses on solving two basic problems associated with modern H.V.A.C applications.

(A) With the focus of modern H.V.A.C systems is to optimize energy efficiency. PID based control is an inherently inefficient method of control for several reasons. A problem with local loop control is that it can be difficult to detect a badly performing loop, because only a few variables in a building will be monitored and the effect of one bad loop may be masked from these variables by other loops that will compensate.

(B) The purpose of building HVAC systems is to maintain comfortable spaces and provide good indoor air quality. A second serious problem with PID (Proportional-Integral-Derivative) control in modern systems is that the operation of various system components is not effectively coordinated.

3. Application of Fuzzy control for optimal operation of complex chilling systems

3.1 Description of the Chilling System

The chilling system described here supplies chill water to the air conditioning systems (AC-systems) installed in basement at Ansal Highway Plaza, Jalandhar (Punjab), India as shown in fig.1. The research conditions are ensured by the AC systems by supplying conditioned air to the building. The amount of cooling power for the building is the sum of internal cooling load (produced by occupants, equipment and computers) and the external cooling load, which depends on outdoor air temperature (Tout) and sun radiation through the windows. The compression cooling method is made use of by the cooling machines installed here. The principle of a compression cooling machine can be described in two thermodynamically processes. In the first step of the cooling process, the heat energy will be transferred from the system to the heat exchanger (evaporator) of the cooling machine, and therefore the liquid gas will evaporate by absorbing the heating energy. After the compression of the heated gas, in the second part of the process, the gas condenses again by cooling the gas through the air cooling system. In that step of the process, the heat transfer is from the condensation system to the outdoor air space. The process is continuous, and based on the second law of the thermodynamics. The vapour compression chiller system consists of following components.

(a) Compressor: It acts as a reclaiming agent.

(b) Condenser and Evaporator: These acts as a heat exchangers.

(c) Expansion Device: It acts as a throttling device to expand the liquid refrigerant.

(d) Refrigerant: It acts as a working fluid which absorbs heat from the fluid to be cooled and rejects heat to the atmosphere, through evaporation and condensation.

The schematic of a vapour compression chiller system is as shown in fig.1

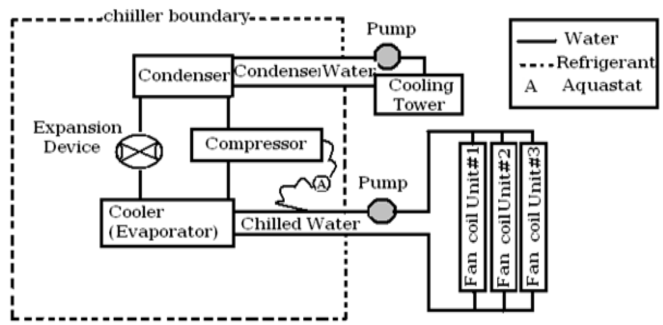

Fig.1: Schematic of a water-cooled chiller system.

During the operation of the cooling machines, the air cooling systems will be used and the condensation energy of the cooling machine is transferred to the outdoor air space. If the outdoor air temperature is much lower than user net return temperature on heat exchanger one, the air cooling system should serve as a free cooling system and replace the cooling machine.

3.2 Thermal analysis of the building and chilling system

The aim of the thermal analysis of the building is to find measurable information for the needed current cooling load. Alternation for internal cooling load of computers and machines could not be exactly registered or measured. It has been proven by measurement of current cooling power of the building as shown in fig.2 that there is not a significant correlation between Tout and the current cooling power. Also, at higher internal load, there is a heat transmission to the outdoor air space, if Tout is lower than 33°C. The current cooling power will increase, if Tout gets higher than 33°C. Although the equipment and computers are on service for 24 hours a day, there is a big alternation of cooling power. In the summer time, when the Tout increases to about 45°C, the current cooling power will be more influenced by Tout. So Tout can be used for forecasting the maximum cooling power. Additional information is necessary, in order to analyze the thermal behavior of the building. This information is gained by measuring the user net return temperature (Tr-un). Any change of total cooling load will influence Tr-un and is an important input for the fuzzy controller.

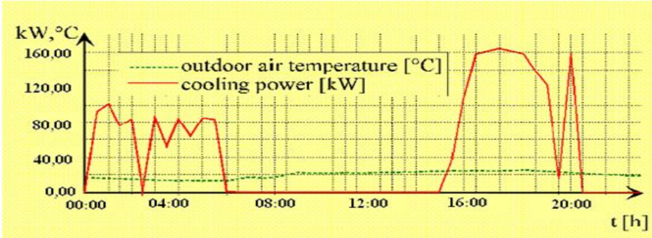

Fig.2: Alternation of current cooling power and outdoor air temperature.

3.3 Requirements for the design of the fuzzy control system

The fuzzy control system is needed to ensure supply of the required cooling power during the operating time of the building by the lowest cost and the shortest system operating time with a low range of set point error for the supply temperature. The concept of knowledge engineering by measurement and analysis of system behavior is necessary, since no expert knowledge has existed for the formulation of the fuzzy rules. Measurement of two physical values of the system is necessary, in order to consider system behavior. These process values are: the outdoor air temperature Tout, which partially presents the thermal behavior of the building, and the user net return temperature (Tr-un), which contains the total cooling load alternation of the building. These requirements focus on three different fuzzy controllers for the different components of the chilling system. The design data for fuzzy controllers has been organized in various tables for the assistance of membership function values of various input variables to a mamdani type fuzzy inference system (FIS).

TABLE-1

FUZZY CONTROLLER'S TEMPERATURE DISTRIBUTION DESIGN DATA

SUPPLY TEMPERATURE (HE_2) °C	SUPPLY TEMPERATURE (HE_1) °C	EXTERNAL TEMPERATURE T_{out} (K) °C
4.2	31.1	29.7
5.8	31.2	30.1
6.3	31.5	33
6.9	31.9	34
7.3	33.2	35
8.2	33.4	37
13	33.5	39
14	34.5	42
15	35.4	54

Here, HE2 and HE1 are the respective heat exchangers for evaporator and condenser and Tout is the outdoor air temperature. The fuzzy controller's set point error difference design data is as shown in table 4.3. Here error (e1) and error (e2) gives the difference between the SP (set point value) & MV (measured value) for condenser and evaporator. Tr-un gives the user net return temperature due to individual zone and internal load (occupants, equipments, computers etc). □Tr-un gives the difference between user net return temperature and set point temperature. □Tout gives the difference between user net return temperature and outdoor air temperature and dTout/dt gives the difference between outdoor air temperature by K^{th} cycle and $K-1^{TH}$ cycle. The assessment of refrigeration is made from the coefficient of performance (COP). It depends upon evaporator temperature Te and condensing temperature Tc.

$$COPcarnot = \frac{Te}{(Tc-Te)}$$

COP in industry calculated for type of compressor:

$$COP = \frac{\text{Cooling Effect (kW)}}{\text{Power input to compressor (kW)}}$$

3.4 Fuzzy controller 1 for operation of the cooling load storage system

The optimum start point for the discharge of the cooling load storage system depends on the maximum cooling power needed, which can differ every day. For calculation of maximum cooling power, Tout must be processed by the fuzzy controller, since the maximum cooling power in the summertime will be influenced extremely by Tout. A feedback of current cooling power calculated by Fuzzy control Block 2 is also necessary, in order to estimate the maximum cooling power. If the peak of a maximum cooling power is estimated by the fuzzy controller, then this will be compensated by optimally discharging the cooling load storage system parallel to the cooling machines.

A mamdani type fuzzy inference system (FIS) is designed in MATLAB software comprising of defining the fuzzy inputs, applying fuzzy operator, applying implication method, aggregating all outputs and defuzzification of aggregate outputs.

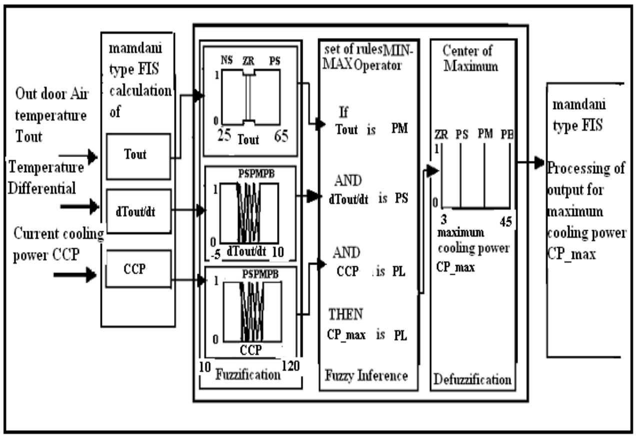

Fig.3: Fuzzy controller 1 for optimally discharging cooling load storage system

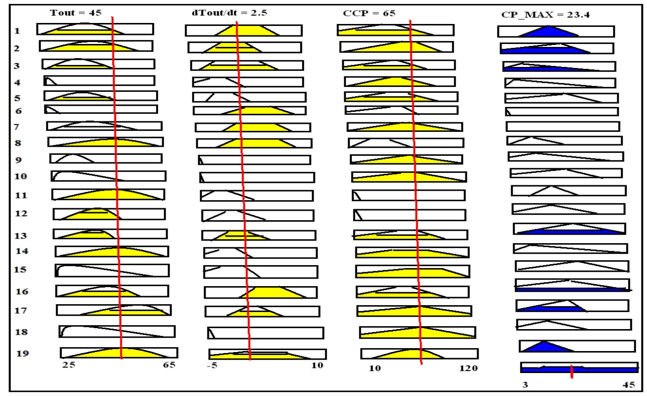

Fig.4: Rule viewer for fuzzy controller

The input variables of the controller 1 are:
(1) Outdoor air temperature Tout
(2) Differential of Tout
(3) Current cooling power of the cooling machines.
For the fuzzification of the Tout, we have following system knowledge. Observation of the system has shown that above Tout of 45°C, a second cooling machine is necessary, in order to meet demand for increasing cooling load. Therefore the fuzzyfication will be around Tout 45°C with only three fuzzy sets. The second fuzzy variable is calculated by eqn (3.1)

$$dT_{out} /dt = (T_{out} (k) - T_{out} (k-1)) \quad (3.1)$$

With Tout (k) = outdoor air temperature by K^{th} cycle.
Tout (k-1) = outdoor air temperature by $K-1^{TH}$ cycle.

The third input variable is the output value of the Fuzzy controller 2, and represents the current cooling power. The output of the fuzzy controller 1 is the estimated maximum cooling power CP-max. The membership function used for the fuzzy variables are available as P, Z, trapmf, trimf and S-functions. For the defuzzification, "Centre of maximum" has been supported by the Mamdani type FIS (Fuzzy Inference System) Fig.4 shows the P membership function as calculated by equation 3.2

$$\mu = MAX\{0, MIN[1, B/(B-C) - AB(1/(B-C)\ (X-A))]\} \quad (3.2)$$

With μ=degree of membership
X= process variable as input variable
A,B,C = parameters for the membership functions in value of the input variable, eg. °C

Membership function P type

The rule viewer for fuzzy controller 1 is as shown in Fig.4

3.5 Fuzzy controller 2 for the operation of the cooling machines

The fuzzy controller 2 (FC-2) is the important part of the optimization control system, so that the cooling potential of the outdoor air is used, before starting any cooling machine. If "e1" is zero, or negative, then the capacity of free cooling system is enough for the required cooling power. The output signal of FC- 2 will be zero. In other cases, FC- 2 is responsible for the operation of the cooling machines. This controller consists of 3 input variables as following:
(1) Set point error" e1" at heat exchanger 1
(2) Set point error "e2" at heat exchanger 2
(3) Difference between user net return temperature (Tr-un) and Tsetpoint
The input variable 1, is calculated as the difference between user net set point temperature (Tset point), and output temperature of the heat exchanger (THE1) according to equation 3.3.

$$e1= T_{setpoint} - T_{HE1}$$

For this variable, only three sets are necessary, in order to define if, e1 is NS, ZR or PS. The range of e1 is between +1k and -1k. The second input variable is calculated as the difference between (T set point), and output temperature of heat exchanger 2 (THE2) according to equation 3.4

$$e2 = T_{set\ point} - T_{HE2} \quad (3.4)$$

The third input variable is determined by equation 3.5

$$\Delta Tr\text{-}un = Tr\text{-}un - T_{set\ point} \quad (3.5)$$

Calculation of □Tr-un is necessary, because Tsetpoint is variable, and therefore □Tr-un contains the real information about the cooling load of the building. As soon as the first variable of the controller "e1" reaches the values of PS or ZR, this indicates that the capacity of FC-system is enough to cover the demanded cooling power, and the output signal for cooling machines is zero. In cases, where the capacity of the free cooling system is not enough, "e" will have values of NS, so that output of the controller will be determined by other rules. In that case the third input variable □Tr-un is more weighted for the output value of the controller, because □Tr-un represents the real alternation of the cooling load of the building. As shown in fig.5, the mamdani type fuzzy inference system (FIS) consists of calculation of input variables such as supply temperature HE1 set point error e1,supply temperature HE2 set point error e2 and user net return temperature □Tr-un, then through the process of fuzzification, fuzzy inference and defuzzification. The processing of output for current cooling power (CCP) takes place takes place in mamdani type fuzzy inference system (FIS).

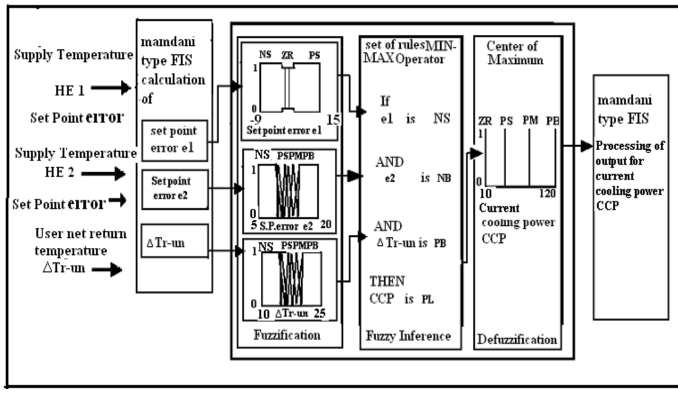

Fig.5: Fuzzy controller 2 for optimal operation of cooling machines

The rule viewer for fuzzy controller 2 is as shown in fig.6

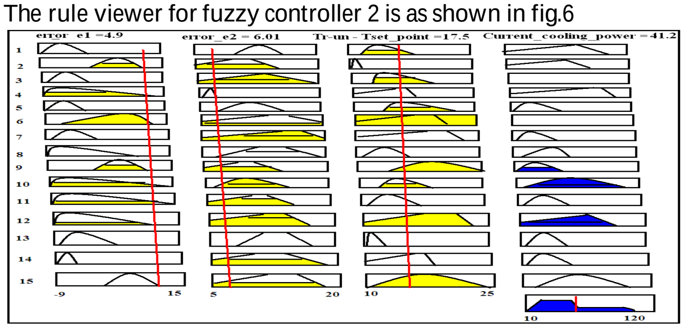

Fig.6: Rule viewer for fuzzy controller

3.6 Fuzzy controller 3 for operation of the free cooling system

This control block is necessary, so that to the cooling potential of the outdoor air is used, and the air cooling systems of the cooling machines are run as free cooling systems. The cooling potential depends on the difference between user net return temperature Tr-un and the outdoor air temperature Tout. The input variables of the control block 3 are:

(1) Difference between Tr-un and set point (□Tr-un)
(2) Set point error 1 at heat exchanger 1
(3) Difference between Tout, and Tr-un (□Tout)

Calculation of input variables 1 and 2 has been explained by control block 2. The third input variable of this controller contains the cooling potential of the outdoor air and is given by equation 3.6.

$$\Delta T_{out} = Tr\text{-}un - T_{out} \qquad (3.6)$$

An important aspect for the formulation of the rules for this controller is the cooling potential of the system, which is represented by the input variable 3, □Tout. The higher the value of this variable is, the fewer FC-system components are necessary in order to supply the demanded cooling power for the building. Fig.7 shows the fuzzy controller block 3.

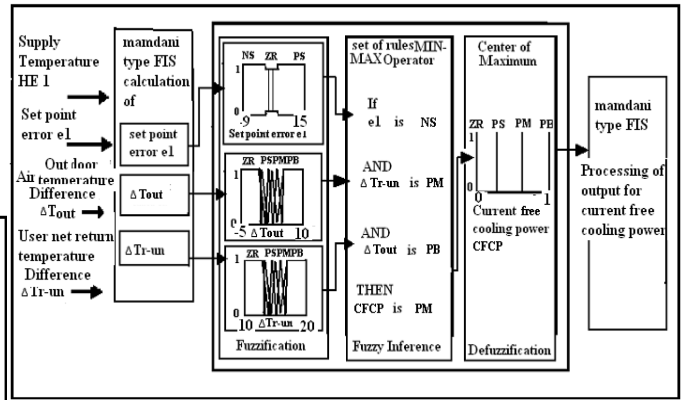

Fig.7: Fuzzy controller 3 for optimal operation of the free cooling system

The rule viewer for fuzzy controller 3 is as shown in fig.8

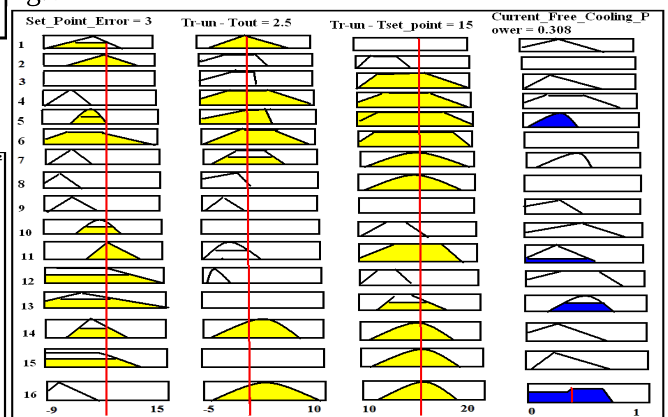

Fig.8: Rule viewer for fuzzy controller 3

Thus the combined fuzzy controller's works in effective coordination with each other in such a way that the output of fuzzy controller 2 i.e. current cooling power (CCP) becomes the input of fuzzy controller 1. Also the inputs to the fuzzy controller 2 become the inputs for the fuzzy controller 3. In this way the controllers gains of three fuzzy controllers can be tuned to match the dynamic characteristics of the vapour chiller system process it is controlling without regard for the other processes. Hence the temperature and pressure outputs in a fuzzy control system results in energy optimization.

The combined fuzzy controllers required for the optimal operation of a complex chilling system is as shown in fig.9

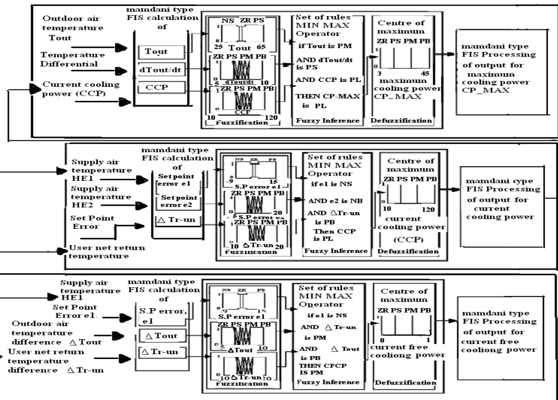

Fig.9: Combined Fuzzy Controllers

4. RESULT AND DISCUSSION

4.1 Results of system optimization by Fuzzy control

The results have been derived from MATLAB/SIMULINK (SIMULATION LINK) library browser comprising of various blocks such as Sinks, Sources, Continuous, Discrete, Discontinuities, Math Operations, Signal Attributes, User Defined Functions, Ports and Subsystems, Signal Routing, Logic and Bit Operations, Lookup Tables, Model Verification, Model Wide Utilities, Additional Math and Discrete blocks. The SIMULINK block diagram showing the comparison between a PID (Proportional Integral Derivative) Controller and Fuzzy Controller is as shown in fig 5.1. Figure 5.2 shows the course of supply air temperature, before the optimization of system operation by PID (Proportional Integral Derivative) control. The alternation of the supply air temperature is between 10.5 °C and 4.8°C. The reason for such a big set point error range lies in the discontinuous operation of the chilling system by a PID (Proportional Integral Derivative) control system. This high alternation of the supply temperature is a reflected image of the alternation of the system status. This unsatisfied system behaviour was realized by Fuzzy Controllers which have the ability of fine tuning the controller gains to match the dynamic characteristics of process it is controlling without regard for the other processes. In this way the various nonlinearities are minimized in a fuzzy control system. Thus effective coordination and adequate operation takes place with the help of fuzzy logic techniques.

The SIMULINK block diagram comprising of various blocks is as shown in fig.10

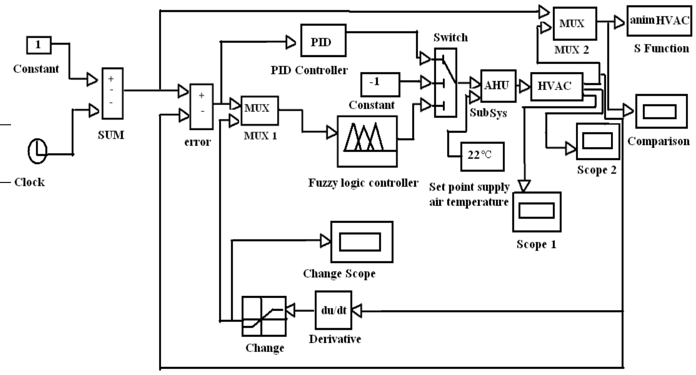

Fig.10: SIMULINK Block Diagram

The set point error discontinuities obtained by operation of the chilling system with PID control system is as shown in fig.11

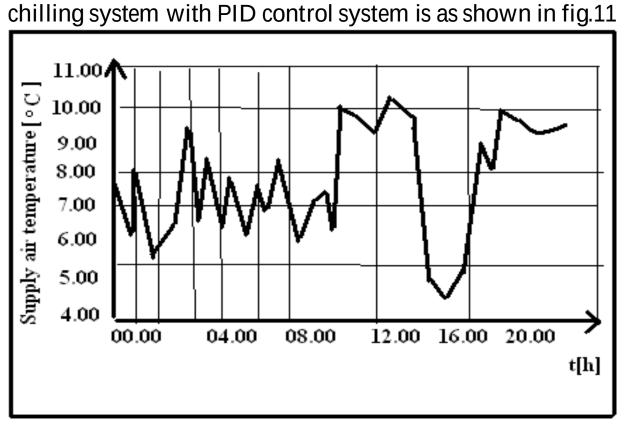

Fig.11: Course of supply air temperature by operation of the chilling system by PID control system

As to the set point error, it can be seen from fig.12 that it is between 6.2°C and 5 °C. This set point error of supply air temperature is a result of the working principle of the compression cooling machines. As the feature of compression cooling machines they have a discontinuous output range for the maximum cooling power, and therefore it is not possible to keep the supply air temperature within a smaller error range as shown here in figure 5.3. The course of the supply air temperature as shown in figure 5.3 indicates a remarkable improvement of the system behaviour. This relatively constant supply air temperature will ensure research and working conditions in the building, by using air conditioning systems in combination with the chilling system.

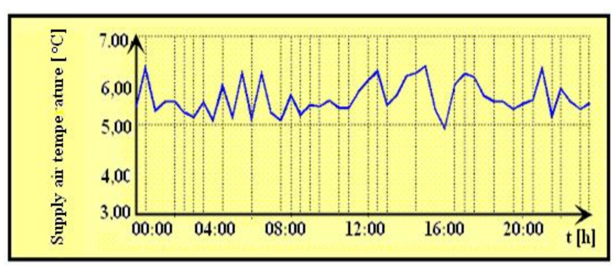

Fig.12: Course of supply air temperature by operation of the chilling system with fuzzy control

Wide acceptance of individual control is predicated on its associated energy cost relative to the conventional approach.

In this implementation, the optimized HIYW "Have-It-Your-Way" has been tested and compared with OSFA "One-Size-Fits-All". Optimized HIYW has also been compared with an optimized version of OSFA in order to get the best-case comparison with optimized HIYW. The optimized OSFA has been constrained to 10% average population dissatisfaction. With ANFIS(Adaptive neuro fuzzy inference system), the set point error of supply temperature is minimized and comes out to be 0.5829 which is less than the set point error 0.6170 as calculated from the trained Sugeno type fuzzy inference system.
The significant potential yearly energy savings through gradient optimization, compared to OSFA are as summarized in fig.13. Here zone1 stands for perimeter shops, zone2 for neighboring shops & zone3 for corner shops.

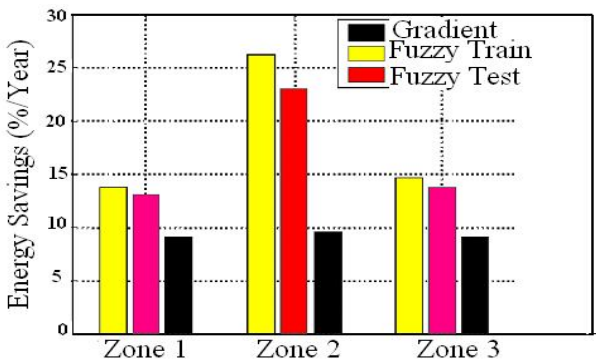

Fig.13: Energy savings per year with respect to OSFA

The energy savings per year with respect to optimized OSFA are as shown in fig.14. It is also shown that a constrained fuzzy approximation is able to mimic these results, thus sensor connectivity requirements are simplified. Energy consumption is strongly related to the cost of building operation, but environmental comfort in a work place, such as a typical cubicle, is strongly related to occupant satisfaction and productivity. Energy consumption and comfort usually affect each other in the opposite way. Unlike the previous studies, individual satisfaction has been the heart of this study. Enhanced thermal comfort and satisfaction has been provided for all occupants, while energy consumption is minimized in our implementation.

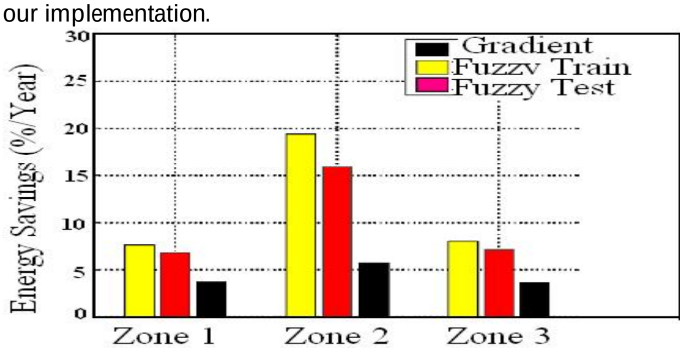

Fig.14: Energy savings per year with respect to optimized OSFA

5.CONCLUSIONS

The research work analyzed a general methodology to evaluate different schemes for dynamic scheduling and optimal control of complex primary HVAC systems that would explicitly include the overlooked aspect of how various uncertainties are to be considered in a decision framework. This methodology would thus consider both the technical system optimization aspect as well as individual preference of those who operate the plant. Conclusion of the present work can be summarized as follows:
(1)Three fuzzy controllers were necessary in order to reach maximum efficiency by operation of different components of the chilling system.
(2)The realized fuzzy control system is able to forecast not only the maximum cooling power of the building, but the cooling potential of outdoor air can also be determined.
(3) Operation of chilling system by fuzzy control enormously reduces the cost of cooling power.
(4) The communication of all sensors with each other is not required in the fuzzy logic approximation for improving occupants comfort & reducing energy consumption.
(5) Reduction of sensor connectivity would reduce system complexity & cost at a modest decrease in energy savings.
(6) Under the real time pricing rates structure, least costs paths are equally least energy paths because no demand charges are considered.
(7) As expected during those hours with low electricity rate, operation of the vapour compression chiller is preferred.
(8) As regards the CV (Coefficient of Variation) of operating cost, model inherenty uncertainty is relatively more important than load uncertainty; however model uncertainty has less effect on probability of loss of cooling capability than load prediction uncertainty.
(9) Results of decision analysis are very much dependent on the relative cooling load capacity & building load profile.
(10) Technologies that reduce the installed cost of building controls & diagnostics can improve their economic attractiveness.

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