OPTIMAL OPERATION OF CHILLER SYSTEM USING FUZZY CONTROL

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Abstract: - Preservation of comfort conditions for buildings' occupants and minimization of energy consumption and cost are the main targets of the energy and indoor environment management systems. This paper aims to achieve those targets by presenting the optimal operation of chilling systems within the building supervisory control systems using fuzzy control instead of a conventional Programmable Logic Controller (PLC) – solutions. An optimal operation means reducing operation time and operation costs of the system; and reducing cooling energy generation and consumption costs. The optimal operation of a chilling system can be achieved using the fuzzy control system. The system addresses the shortcomings of conventional PLC-solutions that occur due to limited abilities of PLC functions with their binary logic. The optimization technique is realized by the use of fuzzy control via the FuzzyTECH®-Fuzzy Design Wizard (FDW) windows. The optimal operation of the system is analyzed using two controllers. The first controller consists of three inputs and one output, whilst the second controller consists of four inputs and one output. The chilling system described here supplies chill water to the air-conditioning systems installed in Universiti Teknologi Petronas (UTP). The data are obtained from the Gas District Cooling (GDC) that handles the operation of the chilling system and generates the chill water. The simulation results of the fuzzy system demonstrate significant improvement in the performance of the chilling system. Future work suggests the implementation of the fuzzy logic system on the target hardware platform, such as programmable logic controllers (PLC) using some special fuzzy logic function blocks.

Keywords: - Chilling system, Air-conditioning system, Optimal operation, Fuzzy control, Fuzzy sets, Membership function, Fuzzy rules.

1 Introduction

Preservation of comfort conditions for buildings' occupants and minimization of energy consumption and cost are the main targets of the energy and indoor environment management systems. Allard et.al. [1] and Fanger [2] discussed the standards regarding indoor comfort, stating the indoor conditions that satisfy users' requirements for indoor air quality and thermal comfort, respectively [3]. Improvements in the airtight insulation in buildings together with the increases in energy required for lighting and office automation equipment, results in excessive capacity of heat and increase the need for air cooling. This then led to an increase in the energy consumption inside the buildings, which then resulted in the increase of the consumption costs. Thus, there is a need for an intelligent system like fuzzy control that can optimize the control operation of this air cooling or chilling system. The optimal operation will ensure a reduction in operation time and operation cost of the system. In addition, it will reduce the cooling energy generation and thus reduce the consumption costs.

Dounis et.al. [4-6] proved the effectiveness of fuzzy techniques in causing a significant reduction of total energy consumption compared to the conventional system. Sierra et.al. [7] presented the advantages of the fuzzy control techniques together with a man-machine interface based on a smart card terminal in satisfying the users preferences. A fuzzy controller was developed and the minimization of energy consumption is achieved by the use of a suitable cost function for the whole system [7]. Using fuzzy techniques, the limited abilities of PLC system used in the current operation of chilling system can be overcome.

The objective of this paper is to design a fuzzy logic controller to optimize the control operation of a chilling system within the building supervisory control systems. It focuses on how to reduce the operation time and how to reduce the cooling energy generation. This paper will consider the two parameters that are not considered in the conventional PLC system, namely, the thermal behavior of the building and the thermal behavior the chilling system. These two parameters are necessary to find the current efficient cooling potentials and methods during the operation. The fuzzy controller design will be in terms of software solutions and will be used in the existing building supervisory control system, with its interface units connected to the chilling system. The data are obtained from the Gas District Cooling (GDC) plant that handles the operation of the chilling system and generates the chill water supplied to UTP.

This paper starts with the components of chilled water system, followed by important theories of fuzzy logic approach. The methodology is then presented followed by results and conclusion.

2 Chilled water system

The chilling system described here supplies chilled water to the air-conditioning systems (AC-systems) installed in UTP. This chilled water is generated by the GDC plant. It has a future cooling capacity of 11,000 RT. The components used in the chilled water system are two Steam Absorption Chillers (SAC) and two Thermal Energy Storage (TES) tanks with four Air Cooled Chillers (ACC).

The main component of the chilled water system is the SAC. SAC is used for main production of chilled water in chilled water system. The SAC system used in this project consists of two SAC of the same capacity and chilled water of 2500 RT can be produced from both chillers. This system consists of cooling water system, steam system and steam condensation water system. Basically, chilled water return (CHR) at 13.5°C from distribution pipe is sent to SAC by pump, and it is cooled to 6°C in SAC and then the chilled water supply (CHS) from SAC is supplied to distribution pipe (customer building). This system mainly provides chilled water with outlet supply of certain temperature (5°C -6°C).

The TES system with ACC are used to reduce the total chiller's capacity by using stored chilled water in TES at peak hours of customer's chilled water demand. The electrical consumption in the plant at the peak hours can then be reduced, due to the reduction of the total chiller's capacity. The TES system consists of one TES tank, four ACC and pumps. The TES has a capacity for 10,000 RTH, and it is able to store chilled water of 5400m^3.

The charging mode of TES is normally run during the “off-peak” period or during night time where the demand is low. The chilled water returned is charged and cooled in order for it to be used on the following day. At this operation mode, electrical chiller is started to chill down the water in the TES tank to increase the calorie to keep the TES storage water at 6°Celcius.

The discharging mode of TES occurred during daytime where the weather is hot and the demand of chilled water is high. At this time, the storage tank discharges the chilled water to the facility buildings. The discharging mode is ready when the TES tank water temperature falls below 6°Celcius. The Distributed Control System (DCS) will prompt the operator guide message to inform the oprator that the TES is ready to discharge. This process is continuous and it helps to ease the high demand of chilled water during daytime. The total volume of chilled water supply is based on the total cooling load demand from the facility building.

Figure 1 shows the schematic diagram of the chilled water system.

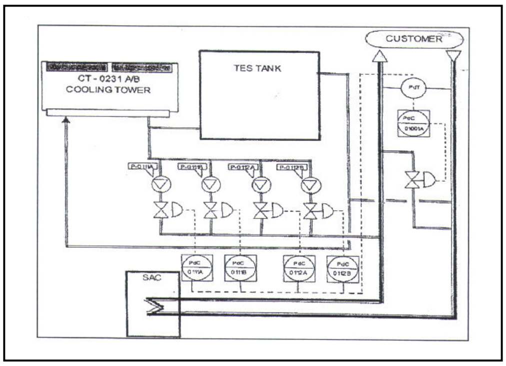


Fig. 1 : Schematic diagram of chilled water system

3 Fuzzy Set Theory

The theory of sets and the concept of a set itself constitute a foundation of modern mathematics. As the mathematical and simulation models of application problems are concerned, they deal with the set theory at the base of mathematics. Usually the set is determined by naming all its members or by specifying some well-defined properties satisfied by it members (the rule method).

The union of two fuzzy sets is defined by:

$$\mu_D(x) = \max\ (\mu_A(x),\ \mu_B(x), x \in X) \quad (1)$$

The intersection of two fuzzy sets is defined by:

$$\mu_D(x) = \min\ (\mu_A(x),\ \mu_B(x), x \in X) \quad (2)$$

The complement of fuzzy sets is given by:

$$\mu_A(x) = 1 - \mu_D(x) \quad (3)$$

4 Fuzzy Rules Processing / Inference Method

Fuzzy rules are the rules of a fuzzy logic system that represent the knowledge of the system. They use linguistic variables as vocabulary, for example to express the control strategy of a fuzzy logic controller. Explaining Fuzzy Rules means to show how to calculate with linguistic concepts. There are two types of fuzzy rules processing, namely, Mamdani and Sugeno methods.

5 Defuzzification Method

The three defuzzification methods used in this work are Fast Center of Area / Gravity (CoA), Center of Maximum (CoM) and Mean of Maximum (MOM).

6 Methodology

6.1 Software Implementation

Throughout the project, FuzzyTECH® software version 5.52 is used. FuzzyTECH® software is the world leading family of software development tools for fuzzy logic and neural-fuzzy solutions. This software is an all-graphical, design, simulation, and optimization environment with implementation modules for most micro controllers and industrial computers. It has been enhanced with editors and functions to support the conventional programming of the PLC. Thus, a user only needs one tool to program both conventional and fuzzy logic parts of the solution. The FuzzyTECH® software combines all necessary editors for membership functions, linguistic variables, rule tables, and system structure with analyzer functions and optimization features. In online-debugging modes, any modification of the fuzzy logic system is instantly translated to the fuzzyPLC without halting. Fig. 2 shows the system architecture of the fuzzy logic approach.

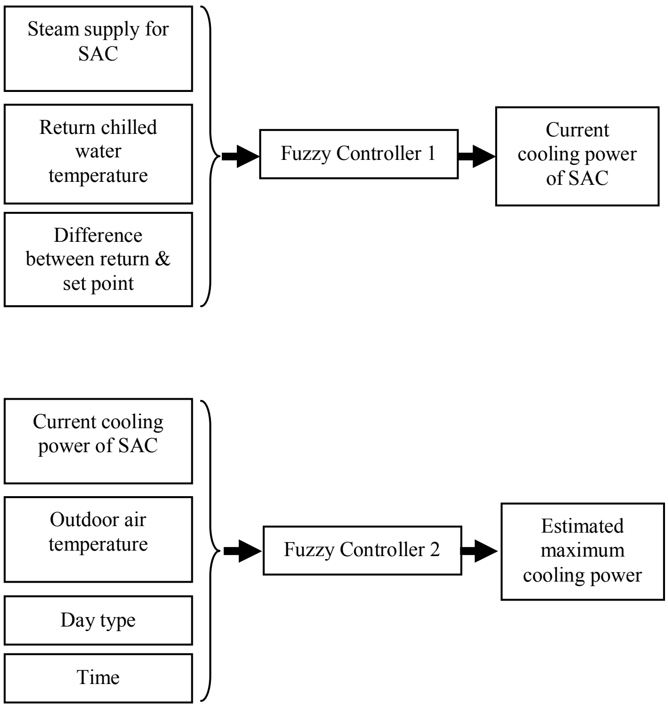


Fig.2: System Architecture of Fuzzy Logic Approach

6.2. Procedure Identification

Fig. 3 illustrates the main processes involved in achieving the optimal operation using fuzzy control system. The input and output relationship is important in designing the fuzzy controller.

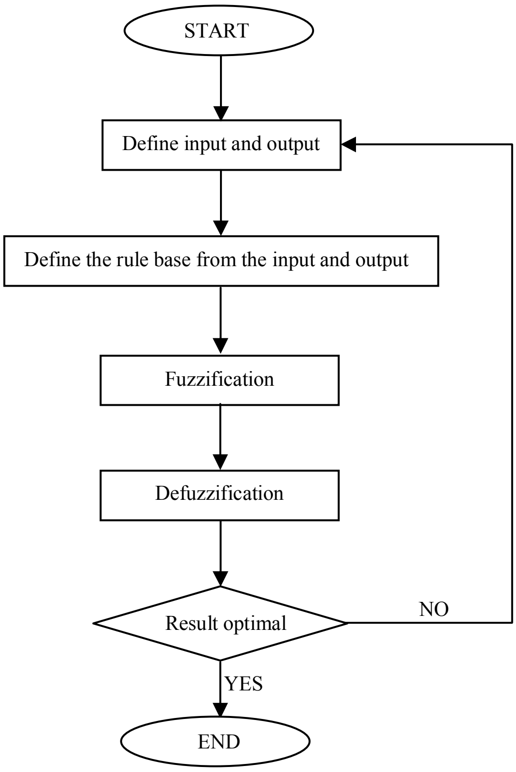


Fig. 3: Flow Chart of simple fuzzy logic

7 Results and Discussions

7.1 Fuzzification Result

Based on the definition of input and output variables, the membership functions of each of the variables were determined.

Fuzzy controller 1 is the important part of the optimization control system, in order to use the cooling potential of the Thermal Energy Storage (TES) tank system. If the return chilled water temperature is low and steam supply is small then the capacity of the TES tank is enough for the required cooling power. The output signal of the fuzzy controller 1 will be small. In other cases, fuzzy controller 2 is responsible for the operation of the SAC. This controller consists of 21 rules with 3 input variables and 1 output variable as follows:

For the first controller, the distribution membership functions that are involved are as follows:

Input variables for controller 1:

Steam supply to SAC	Small, Medium, Large
Return chilled water temperature	Low, Medium, High
Difference between return & set point temperature	Low, Medium, High

Output variable for controller 1:

Current cooling power	Low, Medium, High

For input variable 1, the steam is supply by the steam produced by the Heat Recovery Steam Generator (HRSG) system, which is part of GDC plant system. As the cooling demand increased, the steam supply to the SAC would also increase in order to reduce the return chilled water temperature to its set point. For this variable, only 3 fuzzy sets are necessary.

As for the third input variable, it is determined by equation [4]:

$$\Delta T_{return} = T_{return} - T_{setpoint} \quad (4)$$

Calculation of ΔT_{return} is necessary, because T_{return} is variable and therefore T_{return} contains the real information about the cooling load of the building.

For the fuzzy rules formulation, there are total of 81 rules (full rules block) for fuzzy controller 1, since there are 3 subsets for steam supply, 3 subsets for return chilled water temperature (T_{return}) and 3 subsets for difference between return & set point temperature (ΔT_{return}) and 3 other subsets for the current cooling power. Therefore, total rules are calculated by 3 x 3 x 3 x 3 = 81 rules. However, it can be reduce until 21 rules, when the consideration is only made for partial rules block. This is due to the fact that, for controller 1, every same input variables condition, there have 3 output preference condition (full rule block), which in the real situation only one condition should be chosen (partial rules block).

Fuzzy controller 2 is important for the operation of TES system. The discharge of the TES tank, depends on the maximum cooling power needed, which can differ every day. To know the maximum cooling power, information about the outdoor air temperature (T_{out}) is necessary. A feedback of current cooling power that is realized by the first controller is also necessary, in order to estimate the maximum cooling power. Since the peak of a maximum cooling power is estimated by the fuzzy controller, then this will be compensated by optimally discharging the TES tank parallel to the SAC.

For the second controller, there are total of 4 input variables and 1 output variable. The distribution membership functions that are involved are as follows:

Input variables for controller 2:

Day Type	OFF_Peak_Day,Max Demand _Day, Peak _Day
Current cooling power	Low, Medium, High
Outdoor temperature	Low, Medium, High
Time	Early_Morning, Morning, Noon, Evening, Night

Output variable for controller 2:

Estimated maximum cooling power	Very_Low,Low, Medium, High, Very_High

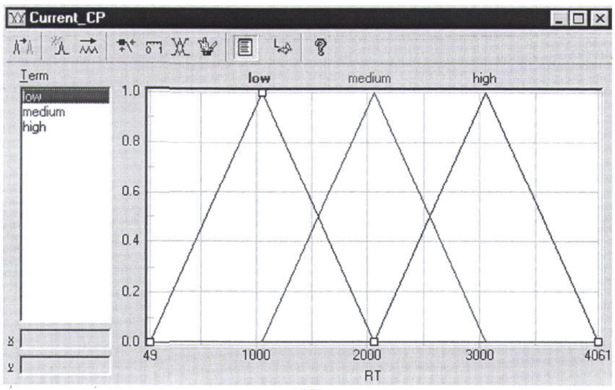
For the fuzzification of outdoor air temperature, observation of the system has shown that, above T_O, of 28°C, the SAC is necessary, in order to meet the demand for increasing cooling load. Therefore for this input variable, there are only 3 sets, which are defined by, Low, Medium and High.

The second input variable is the output value of the fuzzy controller 1 and represents the current cooling power.

The third input variable for fuzzy controller 2 is the time. It consists if 5 sets that define the input as early morning, morning, noon, evening and night. The time is to indicate; at what hour does the cooling load is at higher or lower demand.

The last input for this controller is the day type. This day type is to show that at different day, the cooling load demand from the building is different. For example, at peak and demand day, the cooling load demand might increased, however for the OFF peak day, the demand is much lower. Therefore in is important to include the day type as the cooling load demand varies with it. In this case, there are 3 sets to define the day type.

The membership function for current cooling power is as shown in Fig.4.



(d)

Fig.4: Membership function for input variable-current cooling power

The output of the fuzzy controller 2, is the estimated maximum cooling power. This value will be transformed in to the PLC system, where crisp limits are formulated for the discharge of the TES system.

The total rules for this fuzzy controller 2 are calculated by 3 x 3 x 3 x 5 x 5 = 675 rules. However, it can be reduce until 30 rules, when the consideration is only made for partial rules block. The fuzzy rules for the fuzzy controller 2, in Fig.5.

#	IF Current_CP	Day_type	Time	Tout	THEN DoS	Estimated_Max_CP
1	low	OFF_Peak_Day	early_morning	low	1.00	very_low
2	low	OFF_Peak_Day	morning	low	1.00	low
3	low	OFF_Peak_Day	noon	high	1.00	high
4	low	OFF_Peak_Day	evening	medium	1.00	medium
5	low	Max_Demand_Day	morning	medium	1.00	high
6	low	Max_Demand_Day	noon	high	1.00	high
7	low	Max_Demand_Day	evening	medium	1.00	medium
8	low	Max_Demand_Day	nite	medium	1.00	medium
9	low	Peak_Day	morning	medium	1.00	medium
10	low	Peak_Day	noon	high	1.00	very_high
11	low	Peak_Day	evening	high	1.00	high
12	low	Peak_Day	nite	medium	1.00	medium
13	medium	OFF_Peak_Day	early_morning	low	1.00	very_low
14	medium	OFF_Peak_Day	evening	medium	1.00	medium
15	medium	OFF_Peak_Day	nite	medium	1.00	medium

Fig.5: Example of fuzzy rules developed for the second controller

For advance analyzing purposes, FuzzyTECH® software offers the user with the analyzer mode, which gives the better views of the output condition. Moreover, by using this advance analyzer, user can monitor the debug process and identify which part of the rules is wrong. Fig.6 shows the example of this analyzer mode.

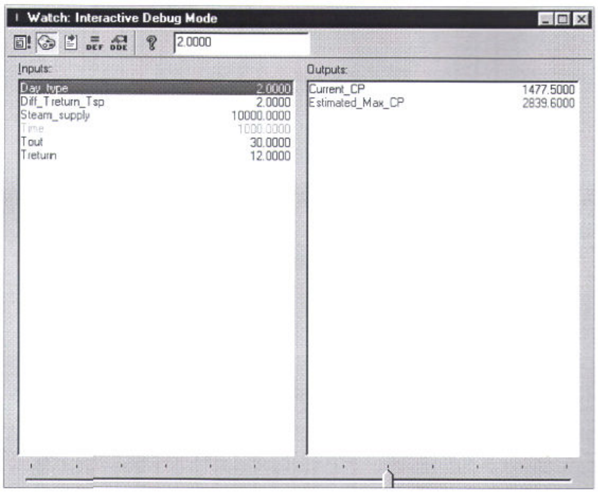


Fig.6: Example of analyzer mode

7.2 Fuzzy Inference Result

In this fuzzy logic approach, the pro and cons of Mamdani and Sugeno methods were analysed and studied. Table 1 shows the data of both methods.

Table 1: Mamdani versus Sugeno

	Mamdani	Sugeno
Similarity	The antecedent parts of the rules are the same	
Difference	The consequent part fuzzy sets	The consequent part are singletons or mathematical function
Advantages	1 Easily understandable by human expert 2 Simpler to formulate rules 3 Proposed earlier and commonly used	4 More convenient in mathematical analysis 5 Guarantee continuity of the output surface
Applications	Good for capturing expertise of human operator	Good for embedding linear controller and effective when the plant model is known

From the analysis, it was found out that, Mamdani method is the most suitable to be used as the fuzzy processing method.

7.3 Defuzzification Result

The objective of a defuzzification method is to derive a non-fuzzy (crisp) value that best contains the fuzzy value of the linguistic output variable. Similar to the different fuzzy processing methods, different methods for defuzzification exist. To select the proper defuzzification method, understanding about the linguistic meaning that underlies the defuzzification process is necessary. The features of the methods were summarized. as shown in Table 2:

Table 2: Summary of the features of defuzzification methods

Item \ Method	**CoA**	**CoM**	MoM
Continuity	Yes	Yes	Yes
Disambiguity	Yes	Yes	Yes
Plausibility	Yes	No	Yes
Computational Complexity	Good	Good	Bad

In this work, CoM was chosen as the defuzzification method, since the method determines the most typical value for each term and then computes the best compromise of the fuzzy logic inference result. To obtain the best compromising value for the result of the fuzzy logic inference as a real number, the inference results are considered "weights" at the positions of the most typical values of the terms. The best compromise is where the defuzzified (crisp) value balances the weights.

7. Conclusion

An optimization strategy for the operation of a complex chilling system is realized by fuzzy control system, and aimed to be implemented into an existing building automation system. In the existing system, the high alternation of the supply temperature exists, due to the alternation of the system status produced by PLC functions, which does not have the ability of fine-tuning for the system operation. Thus this fine-tuning of the system is realized by fuzzy control system. Two controllers with total of 51 rules were developed by using the FuzzyTECH® software, in order to reach the maximum efficiency by operation of different components of the chilling system. Sufficient number of rules is necessary for each controller to fine-tuning the fuzzy control system. The simulations shows a promising result in achieving the optimal operation of the chilling system.

Future work suggests the implementation of the fuzzy logic system on the target hardware platform, such as programmable logic controllers (PLC) using some special fuzzy logic function blocks.

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