ENERGY ANALYSIS OF AN AIR CONDITIONING SYSTEM USING PID AND FUZZY LOGIC CONTROLLERS

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Dedicated to :

My lovely wife, Lusi Nesti, and
My wonderful child, Muhammad Farhan Al Hasan.

My parents :
A.H. Nasution and R. Siregar, Nasrul Rivai and Zirnawati Ijazi

My brothers and sister :
Sutan Nasution, Armansyah Nasution, Nastriyanto Nasution
Elfrina Nasution and family.

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ABSTRACT

Reducing energy consumption and ensuring thermal comfort are two important considerations in designing an air conditioning system. Alternative approach to reduce energy consumption proposed in this study is to use a variable speed compressor. Two control strategies were proposed, which are proportional plus integral plus derivative (PID) and fuzzy logic controllers. An air conditioning system, originally operates on an On/Off control mechanism, was retrofitted to enable the implementation of the controllers. Measurements and computer interface systems were designed and software to implement the controller algorithms was developed using Visual Basic. The system was installed to a thermal environmental room together with a data acquisition system to monitor the temperature of the room, coefficient of performance, energy consumption and energy saving. Measurements were taken during the two hours experimental period at a time interval of five minutes for temperature setpoints of 20, 22 and 24^{o}C with internal heat loads of 0, 500, 700 and 1000W. Each controller was tuned for the best performance. The results indicate that thermal comfort of the room together with significant energy saving can be obtained through a proper selection of controller parameters. Energy analysis shows that PID and fuzzy logic controllers are better than On/Off control mechanism. Generally, fuzzy logic controller is better than PID controllers. However, conventional controllers such as PID or its combinations are still capable of controlling the space temperature with some amount of energy saving but at the expense of the time to tune the controller parameters. A new PID tuning method based on trial and error was therefore proposed. This study shows that using variable speed compressor and choosing suitable control strategy, the space temperature is able to be controlled with significant energy saving.

ABSTRAK

Penjimatan tenaga dan memastikan keselesaan haba adalah dua pertimbangan penting apabila merekabentuk sistem pendinginan udara. Kaedah alternatif yang dicadangkan dalam kajian ini untuk mengurangkan penggunaan tenaga ialah menggunakan pemampat laju bolehubah. Dua strategi kawalan dicadangkan iaitu pengawal berkadaran campur kamiran campur terbitan (PID) dan logik fuzi. Sebuah sistem pendinginan udara yang asalnya beroperasi dengan menggunakan sistem kawalan On/Off telah diubahsuai untuk membolehkan penggunaan pengawal yang dibangunkan. Sistem pengukuran dan antara muka komputer telah direkabentuk dan perisian untuk melaksanakan algoritma kawalan telah dibangunkan menggunakan Visual Basic. Sistem ini telah dipasang di sebuah bilik persekitaran haba bersama-sama dengan sistem perolehan data untuk memantau suhu bilik, pekali prestasi, penggunaan tenaga dan penjimatan tenaga. Pengukuran dilakukan semasa ujikaji yang berlangsung selama dua jam pada sela masa lima minit bagi suhu yang ditetapkan iaitu 20, 22 dan 24^{o}C dengan bebanan haba dalaman 0, 500, 700 dan 1000W. Setiap pengawal ditala untuk memperolehi prestasi terbaik. Hasil ujikaji menunjukkan keselesaan haba bilik tersebut berserta pengurangan tenaga dapat diperolehi melalui pemilihan parameter pengawal yang sesuai. Analisis tenaga telah menunjukkan bahawa pengawal PID dan pengawal logik fuzi adalah lebih baik berbanding dengan pengawal On/Off. Secara umumnya, pengawal logik fuzi adalah lebih baik berbanding dengan pengawal PID. Walaubagaimanapun, pengawal konvensional seperti PID atau kombinasinya masih mampu untuk mengawal suhu ruang dengan penjimatan tenaga yang tertentu tetapi mengambil masa yang lama untuk menala parameter pengawal tersebut. Justeru kaedah talaan PID baru berdasarkan kaedah cuba-cuba telah dicadangkan. Kajian ini telah menunjukkan bahawa melalui penggunaan pemampat laju bolehubah dan pemilihan strategi kawalan yang sesuai, suhu ruangan dapat dikawal dengan menghasilkan penjimatan tenaga yang signifikan.

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LIST OF ABBREVIATIONS

AC	Alternating Current
A/D	Analog to Digital
ADCs	Analog to Digital Converter
AHU	Air Handling Unit
ANSI	American National Standards Institute
ASDs	Adjustable Speed Drives
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CC	Cohen-Coon
COP	Coefficient of Performance
CSI	Six-step Current Inverter
D/A	Digital to Analog
DACs	Digital to Analog Converter
DDC	Direct Digital Control
DX	Direct Expansion
EER	Energy Efficiency Ratio
EEV	Electric Expansion Valve
FAM	Fuzzy Associative Memory
FLC	Fuzzy Logic Control
FOLPD	First Order Lag Plus Delay
HSPF	Heating Season Performance Factor
HVAC	Heating, Ventilating and Air Conditioning
IC	Integrated Circuit
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
IFT	Iterative Feedback Tuning

IMC	Internal Model Control
IPD	Integral Plus Delay
IPLV	Integrated Part Load Value
ISE	Integral Square Error
P	Proportional
PC	Personal Computer
PI	Proportional Integral
PD	Proportional Derivative
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation
NN	Neural Network
SEER	Seasonal Energy Efficiency Ratio
SIMC	Skogestad Internal Model Control
SOSPD	Stable or Unstable Second Order System Plus Delay
TAE	Trial and Error
VRFT	Virtual Reference Feedback Tuning
VSC	Variable Speed Compressor
VSD	Variable Speed Drive
VSI	Six-step Voltage Inverter
ZN	Ziegler-Nichols

LIST OF SYMBOLS

a	:	The intersection of the tangent with the vertical axis
b	:	Feedback
C	:	Capacitor
COP	:	Coefficient of performance
CR	:	Pressure ratio
d	:	Disturbance
D	:	Derivative
e	:	Error
E	:	Rated voltage
Eff	:	Motor efficiency
f	:	Frequency
G	:	Transfer functions
h	:	Enthalpy
hp	:	Rated horsepower
I	:	Current
I	:	Integral
k	:	Steady state gain
K	:	Controller parameters, gain
L	:	The intersection of the tangent with the horizontal axis
m	:	Manipulated variable
$\overset{o}{m}_r$	:	Mass flow rate
P	:	Pressure, Power, Proportional
PB	:	Proportional band
PF	:	Power factor
Q_c	:	Heat rejection
Q_e	:	Refrigeration effect

Q_r	:	Refrigeration capacity
r	:	Reference value
R	:	Resistor
s	:	Entropy
t	:	Time
T	:	Temperature, Time constant, Period
u	:	Controller output
U	:	Conversion value, Universe of discourse
v	:	Specific volume
V	:	Voltage, Analog output
W	:	Work input to the compressor
x	:	Universe of discourse
y	:	Controlled variable, output
z	:	Universe of discourse

Greek Symbols

Δt	:	Sampling interval
Δe	:	Rate-of-change-of-error
ΔZ	:	The motor speed change
η	:	Efficiency
λ	:	Adjustable parameter
μ	:	Membership function

Subscript

1, 2, …, n	:	Points measurements
abs	:	Absolute
c		Controller, Critical

cal	:	Calculated
con	:	Consequent
com	:	Compressor
d	:	Plant, Derivative
D	:	Derivative
el	:	Electrical
f	:	Liquid
fg	:	Mixture
g	:	Gas
i	:	Integral
I	:	Integral
max	:	Maximum
out	:	Output
p	:	Sensor, Proportional
r	:	Reduced
ref	:	Reference
s	:	Isentropic
u	:	Ultimate

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CHAPTER 1

INTRODUCTION

1.1 Introduction

With rising living standards and expectation for thermal comfort, air conditioning has gradually come to be considered a necessity. This can be seen from the fact that the number of air conditioning system used has increasingly become common. Consequently the increase use of air conditioning system has had a significant impact on the total amount of energy used. However, the current design standards and practice for air conditioning are in fact fundamentally based on the principle of maintaining thermal comfort. Investigation by Yu (2001) showed that 67% of the respondents claimed that they intentionally oversized air conditioning design for about 10 to 15% because of the following reasons :

1. For future extension, renovation and change of usage.
2. Too much uncertainty and assumptions in the preliminary design stage.
3. As a contingency plan.
4. Plant performance deteriorate as a result of aging.
5. At the request of the client.

However, good engineering practice should not oversize the plant but design for flexibility. The consequence of oversizing is paying extra cost for running the plant with low efficiency. If there is possibility of future extension or change of usage, the system should be so designed such that it will be easy and inexpensive when adding or changing equipments.

An air conditioner works by transferring heat from the air inside the air-conditioned space to the outside atmospheric air. The heat is transferred to the refrigerant in the evaporator (inside the cooled space) and then transferred out of this refrigerant in the condenser (outside the cooled space). The refrigerant is pumped from the evaporator to the condenser by the compressor. The compressor is the main consumer of energy in a refrigerated air conditioner while blowers consume much lesser energy. The electric power consumption of the compressor accounts for about 90% of the total electric power consumption of an air conditioner (Tojo *et al*., 1984).

An air conditioning automatic control system or simply a control system, primarily modulates the capacity of the air conditioning equipment to maintain a predetermined condition defined by several parameters within an enclosure or for the fluid entering or leaving the equipment to meet the load and climate changes at optimum energy consumption and safe operation. The predetermined parameter to be controlled is called the controlled variable. In heating, ventilating and air conditioning (HVAC), the controlled variables can be temperature, relative humidity, pressure, enthalpy, fluid flow, etc.

Due to the large number of buildings that use air conditioning units along with other electrical appliances, the amount of energy consumption from this sector is significantly high. Obviously there are a lot of opportunities for considerable energy saving by using variable speed drives of the motor compressor. Variable speed drives allow loads driven by alternating current (AC) induction motors to operate in a wide range of speeds compared with fixed speed motor.

With respect to these opportunities, current research is focused on energy and compressor performance of an air conditioning system using proportional-integral-derivative (PID) and fuzzy logic controller. The main idea of designing the controller is to maximize energy saving for an air conditioning system application through variable speed drive control.

1.2 Research Problem

HVAC systems play several roles to reduce the environmental impact on buildings. The primary function of HVAC systems is to provide healthy and comfortable interior conditions for occupants. The goal of HVAC control system design is to provide good control strategies to maintain comfort for the occupants of a building under variable load conditions with minimal use of energy. Reducing energy consumption becomes one of the most important aspects in HVAC control system design because of the fact that 50% of the world energy is consumed by HVAC equipment in industrial and commercial buildings (Imbabi, 1990; Hensen, 1995).

Most air conditioning systems for countries located in the tropics operate at constant compressor speed as these countries experience a quite moderate diurnal temperature variation of the order of 5 - 10^{o}C throughout the year. The temperature inside the building is maintained constant using a simple On/Off system to the air-handling unit (AHU). In many cases, no proper control system is used to conserve energy. The selection of these systems for most application is mainly based on capital cost of the equipment and the use of control system to conserve electrical energy is not of prime importance.

In cases where accurate control of temperature of an environment is needed, for example in manufacturing of electronic components, cooling and dehumidifying of air is accomplished through heating and cooling of air to the required conditions in the air handling unit. Currently, there is a wide concern about the optimum use of energy in buildings, as the price of fuel has doubled in the last five years. Energy conservation and thermal comfort in buildings are topics of specific interest.

One of the methods that has been suggested and investigated to maintain thermal comfort of an environment room and to reduce energy consumption from an air-conditioning unit is through the use of well-tuned controller for the air handling unit and variable speed compressor (VSC). This involves the development of various types of controller either for AHU or the compressor system. Among many control methods for HVAC application, the PID algorithm is very common. For example, Nesler and Stoecker (1984) reported the behavior of the proportional and integral constants in combination to provide responsive, yet stable, control in the HVAC system. Three-way bypass valve was used in this study and the results are valid for valve controller application. Ho (1993) developed and evaluated software package for self-tuning of three-term direct digital control (DDC) using a searching technique for optimization. A simulation model for a practical air-handling system was studied. The behavior under a conventional system of PID controllers was investigated. A new controller based on system identification model was developed and tested where input and actuating variables were incorporated into the system identification model. This model could predict the new system status based on past records and suggest the optimum control actions. Computer simulation had proved that such system identification based controller is superior to the conventional PID controller in at least three major aspects: adaptation to system change, response rate and energy conservation. The result of the study has not been tested for variable speed compressor and may be valid for only AHU controller mechanisms.

Krakow *et al*. (1995) investigated the use of PID controller on an AHU and a compressor of an air-conditioning unit. Such methods were shown to be suitable for attaining compressor and evaporator fan speeds such that sensible and the latent components of the refrigeration system capacity equals the sensible and latent component of the system loads. The investigation also indicated that the space temperature and humidity were not successfully controlled simultaneously by the variation of evaporator fan speed and compressor speed, respectively. Furthermore, the study did not include energy and performance analysis of the air-conditioning unit.

Thermal comfort standards are required to help building designer to provide an indoor climate that building occupants will find thermally comfortable. The definition of a good indoor climate is important to the success of a building, not only because it will make its occupants comfortable, but also because it will decide its energy consumption and thus influence its sustainability (Nicol and Humphreys, 2002). The energy required for climate control is an obvious target for potential reductions (Kathryn and Nicol, 2002).

Thermal comfort is generally listed by occupants as one of the most important requirements for any building. In addition, there is evidence that thermal comfort of occupants is closely linked to their perception of indoor air quality and work productivity. Comfort is a natural need of human being and occupants of a room will react to any change of condition by taking actions to restore their comfort. Discomfort can also lead to high-energy responses which are not sustainable (Santamouris, 2003).

This research work aims at quantifying the performance an air conditioning system operating on an inverter and a controller installed to vary the speed of the compressor for load matching and thermal comfort. The emphasis is on the energy consumption using PID and Fuzzy logic controllers.

1.3 Objectives of Study

Air conditioners are the necessities of life at home, in an office and in public enclosed areas due to the natural demand for comfort in the thermal environment of living or working space in modern society. The conception of controlled thermal qualities of space has developed from conventional air conditioning system to a variable speed air conditioning system.

The existing air conditioner that operates using constant speed motor, produces a very low room temperature which is below the comfort level. While a variable speed air conditioner is a system that could vary the cooling capacity and the room temperature may be controlled. The laboratory tests in this research work carried out can be classified into two categories :

1. Constant speed.
2. Variable speed.

Test on constant speed is to analyze the actual working performance and energy consumption of the system. The aim is to provide reference data on the compressor performance, these data will provide information on the range of the temperature setpoint, the air handling unit performance and estimation of power and energy used. The second test is on variable speed system. This research focused on variable speed using On/Off, PID (such as P, PI, PD and PID) and fuzzy logic control systems. The overall objective behind this research is to design and develop a controller based on computerized system for thermal comfort and energy saving for air conditioning systems application. In this research, a digital On/Off, PID and fuzzy logic control algorithm is applied.

The detail objectives of the research are shown in Figure 1.1. The verification of the main objectives is presented in Chapters 3, 4, and 5 for constant speed, On/Off and PID control and fuzzy logic control, respectively.

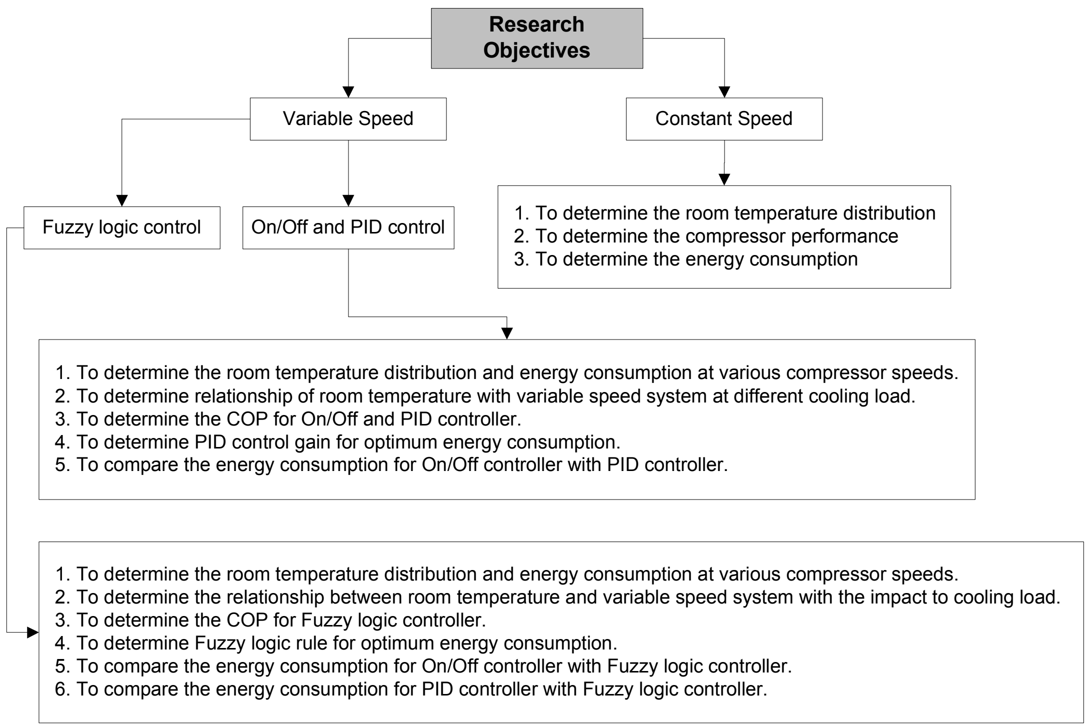

Figure 1.1 The research objectives

1.4 Research Methodology and Scope

1.4.1 Research methodology

The work involved design, development and implementation or application of hardware and software respectively for the constant and variable speed control systems. This is shown in Figure 1.2. It was divided into four phases. The first phase, was designing the equipments to support hardware and software for the controller system which is described in Chapter 3. Softwares such as On/Off, PID and fuzzy logic controls are described in Chapters 4 and 5. The hardware and software were installed and calibrated before performing the experiments. The communication between the hardware and software is displayed on the monitor. Calibrations can be done by sending signals to and from the hardware and software. Detailed information on the calibration is provided in Appendix A.

The second phase, was testing the constant speed compressor system. The actual working performance of the system running under one fixed compressor speed without any capacity control and internal heat load was analyzed. Test on compressor with different frequency setting was conducted prior to analyzing performance of variable speed of compressor system. The aim was to provide reference data for the variable speed motor. These data will provide information on the range of temperature setpoints, voltage and current of the motor, and estimation of power and energy used. The experiment were conducted under constant speed and is described in Chapter 3.

Furthermore, the third phase was the testing of the variable speed control of the compressor system to analyze the actual working performance, energy consumed and the potential energy saving. The performance tests for variable speed control system were conducted based on different temperature setting and internal head loads. The room temperature was controlled using On/Off, PID and fuzzy logic controller. Detailed information on the tuning methods, the experiment and the controller option for all controllers are provided in Chapters 4 and 5.

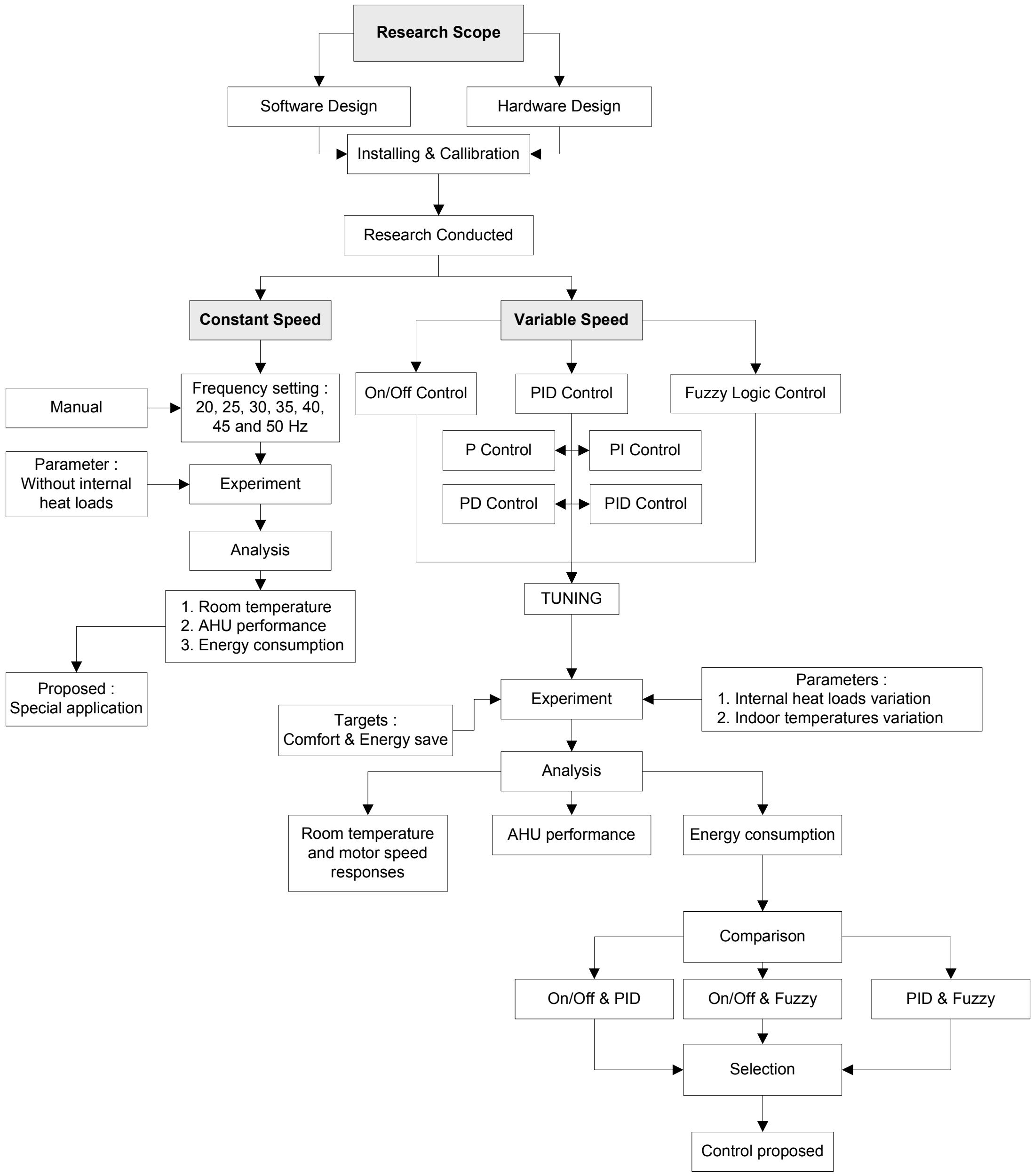

Figure 1.2 The research methodology and scope

After computer technology entered the control world, especially after the control oriented single chip microprocessor was introduced, it has already become feasible and practical to realize On/Off, PID and fuzzy logic control with the aid of software. It has been proven that this way is more flexible and reliable. In this research, a digital On/Off, PID and fuzzy logic control algorithms were applied. All controllers being developed in a separate software with an option to select the desired controllers. The control algorithm was written in Microsoft Visual Basic 6.0. This software was developed to process, collect, store, and display data of the hardware such as ICs temperature sensors, thermocouple, inverter and data acquisition system. The software structure is the one that lets user to interact with the controller by looking at current settings, changing gains and setpoints and others. The interaction between user and the controller parameters is done online and as a result it makes the controller tuning process easier. This section attempts to define certain terms pertaining to the software programs used in the control setup.

In the fourth phase, the final work of the research was the analysis of experimental results such as: temperature and motor speed responses, the compressor performance in term of coefficient of performance (COP) and energy analysis for all controllers. The findings of the study are discussed and reported in this thesis. Conclusion and contributions of the study are drawn and future works are recommended.

1.4.2 Research scope

The scope of this research which can be summarized as follows :

1. To developed from conventional air conditioning (i.e. On/Off control) to variable speed air conditioning system by using PID and fuzzy logic control.
2. On/Off control design :
    a. Digital controller.
    b. Typical control is closed-loop (single-input-single-output).
    c. The upper and lower limit of the motor speed is 1420 and 0 rpm, respectively.
    d. Fixed temperature differential of controller is 1^{o}C.
3. PID control design :
    a. Digital controller.
    b. Typical control is closed-loop (single-input-single-output).
    c. Controller modes are proportional (P), proportional-integral (PI), proportional-derivative (PD) and proportional-integral-derivative (PID).

   d. Tuning of controller parameters (such as: K_p, K_i and K_d) using trial-and-error method.
4. Fuzzy logic control design :
   a. Digital controller.
   b. Typical control is closed-loop (single-input-single-output).
   c. Two input and one output fuzzy variables. The fuzzy input variables are the error between the reference and the measured temperature. And the delta error is the rate of change of the error. The output fuzzy variable is the voltage signal to the motor.
   d. The membership function used is triangular type.
   e. To defuzzify the fuzzy control output into crisp values, the centroid defuzzification method is used.
   f. Tuning method is rule refinement.
   g. The FAM rules are a 3×3 matrix.
5. The experimental settings were :
   a. Temperature setpoints = 20, 22 and 24^{o}C.
   b. Internal heat loads = 0, 500, 700 and 1000 W.
6. Thermal environmental room conditions :
   a. The walls of the room were constructed with new insulations.
7. Analysis and evaluation for all controllers such as: the room temperature, compressor performance in term of COP, energy consumption and energy saving to select the best controller.

1.5 Thesis Outline

The thesis contains six chapters. Chapter 1 is the introduction that highlights the importance of the study.

Chapter 2 presents the literature review. The review focuses on the research and development on the performance of air conditioning system, variable speed control of compressor and control system for air conditioning. Gaps are identified and that justify the objective and methodology of the study undertaken.

Chapter 3 presents the experimental procedure and system characteristic. This chapter describes the development of an integrated hardware to the existing constant speed motor for the compressor such that speed variation is possible. Various instruments are required for measurement of the system and the description of each instrument is given.

Chapter 4 presents classical control theories such as On/Off and PID control, implementation and the controller design approach. The characteristic of the control system, the existing digital On/Off and PID control algorithm, the software development, the tuning method, analysis of the experimental results, controller option and comparison with other works are discussed in this chapter.

Chapter 5 presents a review and introduction to the fundamentals of fuzzy sets. It also shows the use of fuzzy sets in membership functions and discusses the linguistic variables of fuzzy logic. The basic design of fuzzy controller, the software development and the tuning methods are discussed in this chapter. The result of the fuzzy logic controller is discussed and compared with On/Off and PID controllers.

Chapter 6 presents the conclusion, research contributions and recommendations for future research.

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