VARIABLE CAPACITY CONTROL STRATEGY FOR AN AUTOMOBILE AIR CONDITIONING SYSTEM

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Dedicated to:
My beloved wife Amirah Haziqah Binti Zulkifli, and
my daughter, Aisyah Haziqah Binti Afiq Aiman

My parents:
Dahlan Bin Sam and Rudziah Binti Fadil

My brothers and sisters:
Arif Aiman Bin Dahlan, Siti Khairunnisak Binti Dahlan and
Siti Khairun Nabiha Binti Dahlan

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ABSTRACT

Conventional vehicle air conditioning system often uses an engine-driven compressor where it operates according to engine speed. This causes cooling capacity fluctuation that leads to low passenger thermal comfort. Furthermore, designers usually oversize the air conditioning system to speed up the cooling time, regardless of the ambient condition and vehicle speed, which leads to high energy and fuel consumption of the vehicle. Thus, this research investigates the feasibility of independent electric direct current (DC) compressor retrofit into conventional petrol vehicle air conditioning system and while developing an intelligent fuzzy logic controller (FLC) for better control of the vehicle compartment temperature and lower the fuel consumption. This study was implemented on a compact passenger vehicle with original engine-driven compressor air conditioning system. First, the average cabin temperature, air conditioning performance and fuel consumption of the vehicle with original engine-driven compressor was obtained. Second, the DC compressor was retrofitted and the original on/off controller was used. The steady-state vehicle compartment temperature was also measured at various DC compressor speed to support the development of the FLC for variable speed control (VSC). Next, the VSC was implemented and all the data were compared. The experiments were carried out on a chassis dynamometer (or called rolling road) with variable internal heat load and temperature setting. The results indicate that the variable capacity control strategy on the DC compressor with the FLC control system give positive results, with lower fuel consumption, higher coefficient of performance (COP) and enhanced temperature control compared to engine driven compressor with on/off controller and DC compressor with on/off controller. The implementation of the intelligent DC compressor system gives higher energy efficiency to vehicles while providing better temperature control, thus enhancing the driving experience.

ABSTRAK

Sistem penyaman udara kenderaan konvensional selalunya menggunakan pemampat yang dikendalikan oleh tali sawat yang bersambung dengan enjin kenderaan. Ini menyebabkan kapasiti penyejukan tidak stabil yang membawa kepada keselesaan terma penumpang yang rendah. Tambahan pula, pereka sistem biasanya membesarkan saiz penghawa dingin untuk mempercepatkan masa penyejukan dalam apa jua keadaan persekitaran dan kenderaan kelajuan, yang mengakibatkan penggunaan tenaga dan bahan api kenderaan menjadi tinggi. Oleh itu, kajian ini menganalisis kemungkinan penggunaan pemampat bebas arus terus elektrik (DC) pada sistem penghawa dingin kenderaan konvensional yang menggunakan bahan api petrol, dan juga untuk membangunkan kawalan pintar fuzzy logic (FLC) untuk kawalan suhu kabin kenderaan yang lebih baik dan penggunaan bahan api yang lebih rendah. Kajian ini dijalankan ke atas kenderaan penumpang jenis padat yang asalnya menggunakan pemampat dikuasakan oleh tali sawat. Pertama, data purata suhu kabin, prestasi penyaman udara kenderaan dan penggunaan bahan api pemampat dorongan enjin asal diperolehi. Kedua, pemampat DC dipasang dan pengawal buka/tutup yang asal telah digunakan. Ukuran suhu mantap kabin kenderaan juga diambil pada beberapa kelajuan pemampat DC untuk menyokong pembangunan FLC untuk kelajuan berubah-ubah (VSC). Seterusnya, VSC dipasang dan semua data dibandingkan. Ujikaji telah dijalankan pada dinamometer jenis roda dengan pelbagai beban haba dalaman dan suhu titik set. Keputusan kajian membuktikan bahawa kabin kenderaan yang menggunakan pemampat DC dengan sistem penghawa dingin pintar memberikan keputusan yang lebih baik, dengan penggunaan bahan api yang lebih rendah, pekali prestasi (COP) yang lebih tinggi dan kawalan suhu yang lebih tepat berbanding pemampat dorongan enjin dengan kawalan buka/tutup dan pemampat DC dengan kawalan buka/tutup. Pelaksanaan sistem pemampat DC pintar memberikan kecekapan tenaga yang lebih tinggi kepada kenderaan sementara memberikan kawalan suhu yang lebih baik dan ini seterusnya meningkatkan pengalaman pemanduan.

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LIST OF ABBREVIATIONS

AC	Alternating Current
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
COP	Coefficient of Performance
DC	Direct Current
FAM	Fuzzy Associative Memory
FLC	Fuzzy Logic Control
HVAC	Heating, Ventilating and Air Conditioning
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation
VSC	Variable Speed Control
EER	Energy Efficiency Ratio
SEER	Seasonal Energy Efficiency Ratio
IPLV	Integrated Part Load Value
EEV	Electric Expansion Valve
LCD	Liquid Crystal Display

LIST OF SYMBOLS

Δe	Rate-of-change-of-error
ΔZ	The motor speed change
a	The intersection of the tangent with the vertical axis
b	Feedback
e	Error
I	Current, Ampere
km	A distance parameter
litre	The volume parameter
Qe	Refrigeration effect
Qr	Refrigeration capacity
R	Resistor
s	Entropy
U	Conversion value, Universe of discourse
V	Voltage output (Voltage)
v	Specific volume
W	Work done (Work)
x	Universe of discourse
z	Universe of discourse

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CHAPTER 1

INTRODUCTION

This chapter explains briefly the development of variable capacity control strategy for an internal combustion engine vehicle air conditioning system retrofitted with direct current (DC) compressor and implementation of variable speed control (VSC) system through an intelligent control of fuzzy logic controller (FLC). Problem statements, objectives, scopes, project implementation flowchart, significance of research and overall thesis outline are explained in this chapter.

1.1 Introduction

Increased emphasis on fuel saving of vehicle via climate control system is rapidly growing due to high consumer demand and competition between manufacturers. Manufacturing a vehicle with the lowest fuel and energy consumption requires minimal parasitic load from the vehicle power plant without sacrificing passenger's thermal comfort. Concurrently, the capital cost of the vehicle must still be appealing to the consumers.

Currently, non-electric internal combustion engine vehicle air conditioning system uses an engine-driven compressor that is powered by the engine where the compressor rotates at the same engine rotational speed using belting system causing cooling capacity of the system to fluctuate according to the driving conditions. Moreover, the size of air conditioning system is often oversized to ensure fast cooling time of vehicle compartment regardless of engine speed. Thus, under normal weather conditions, a lot of energy is wasted which results in high average vehicle fuel consumption.

Therefore, attention has been drawn towards designing and building a variable capacity control strategy for an internal combustion engine vehicle air conditioning system retrofitted with DC compressor and implementation of VSC system through an intelligent control of FLC to control compressor operation for optimum energy consumption according to temperature setting. Up until now, such system has been sparse and not commercially available. The use of FLC in controlling the DC compressor speed is seen to further increase the system's efficiency, thus lowering the fuel consumption and increase passenger's thermal comfort.

This thesis focus on the development and design of an air conditioning system in non-electric internal combustion engine vehicle using DC compressor with the implementation VSC to increase the performance and decrease the vehicle fuel consumption. Investigations was done experimentally system to obtain air conditioning performance and fuel consumption characteristics to provide enhanced load-matching capability using FLC to achieve the desired temperature setting. The experimental setup was made in the actual vehicle with various internal heat load and vehicle speed to emulate actual conditions.

1.2 Problem Statement

The heating, ventilating and air conditioning (HVAC) system in a vehicle purpose is to provide comfortable interior conditions for passengers with good control strategies to maintain thermal comfort for passengers inside vehicle compartment under variable thermal load conditions with low energy and fuel consumption (Chen *et al.*, 2006). Reducing energy and fuel consumption are two important aspects to focus in developing HVAC system (Bevilacqua, 1999). A study by Farrington shows that vehicle air conditioning system is the largest auxiliary load in vehicle where it can increase fuel consumption up to 20% during standard driving cycle in summer depending on type of vehicle (Farrington *et al*., 2003).

Conventional internal combustion engine vehicle air conditioning systems operate by using engine-driven compressor which results in different cooling capacity as the compressor speed changes with a wide range of engine speed (Li *et al*., 2004). The compressor operation causes fluctuation of conditioned air temperature inside vehicle compartment and therefore the system consume higher energy consumption than necessary (Hendricks, 2001). The mechanical power used by the compressor increases proportionally as the compressor speed increases with the engine speed although the cooling efficiency remains constant, decreasing compressor efficiency (Kaynakli and Horuz, 2003).

Air conditioning system in vehicles is often oversized to quickly lower the temperature inside vehicle compartment even at low engine speed. The cooling capacity of around 6 kW in vehicles is drastically oversized over the common 3 kW heat load in summer condition (Rugh *et al*., 2004). Power input of the engine-driven compressor in current vehicle with engine-driven compressor air conditioning system cannot be controlled directly so therefore, it is either the compressor are turned on and off or the cooled air is heated via engine coolant system (Ratts and Brown, 2000).

The impact of vehicle air conditioning system to the fuel consumption is enormous. A 34 km/l vehicle is reduced to only 21.26 km/l if the auxiliary load increase from 400 W to 2000 W and further decreased to 15.31 km/l with auxiliary load of 4000 W (Farrington and Rugh, 2000; Bharathan *et al*., 2007). The fuel consumption of vehicles is also increased from the usage of air conditioning between 20 to 50% according to the size and engine efficiency (Farrington and Rugh, 2000). Thus, as the vehicle air conditioning system is the highest auxiliary load in a vehicle after alternator, the load must be decreased without compromising the thermal comfort of passengers inside the vehicle.

A study by Ratts and Brown (2000) indicates that the air conditioning system performance degrades as the vehicle speed increases. An 18% increment of thermodynamic losses occurs when vehicle speed increases from 48 km/h to 96 km/h. As the engine-driven compressor speed increased with increasing engine speed and vehicle speed, the refrigeration system's losses increase and most of it is coming from the compressor itself. The research also concludes that by using a compressor that reduce or eliminate the compressor cycling, better efficiency could be achieved.

Increase concern on the optimum use of vehicle fuel consumption among manufacturers and end-user as the cost of fossil fuel has increased and one of vehicle buyers concern is on fuel consumption. Energy saving of vehicle and thermal comfort in vehicle compartment are topics of definite interest. There are many researchers that focus on the topic of vehicle air conditioning system to achieve better overall fuel consumption as this system is remains the highest auxiliary energy consumption inside a vehicle.

Variable speed refrigeration system minimized the transient behaviour and steady state errors of the system. Conventional on/off controller is mostly used by designers to control the cooling capacity of the air conditioning system either for vehicle or residences (Aprea and Renno, 2009). The big drawback of this method is its current peaks during on/off operation (Aprea and Renno, 2009).

Problem with conventional on/off controller is the temperature fluctuation causing higher uncertainties in the system parameters and limited operation point of refrigeration systems, which greatly reduce energy efficiency and further contribute to higher vehicle fuel consumption (Ekren *et al.*, 2013). The usage of nonlinear intelligent controller based on FLC may overcome this issue (Aprea *et al*., 2004; Hamed, 1999).

Manufacturers designed the vehicle air conditioning system for most of their products by using a simple on/off controller to maintain the temperature inside vehicle compartment. Capital cost of the material used for the control system is the main concern, where reducing energy consumption and fuel consumption is not of prime importance (Nasution, 2006).

Thermal comfort is very important for passengers inside vehicle compartment as it is considered as enclosed area (ASHRAE, 2004). Study proves that passenger's thermal comfort is correlated with driver stress level while driving at any climate conditions (Farrington *et al*., 2004). Passengers inside the vehicle compartment will react to achieve and restore their very own need of thermal comfort (Rugh *et al*., 2004).

During engine idling, the engine consumes high air-fuel ratio because it does not work at normal operating temperature thus causing high brake-specific fuel consumption and imperfect fuel ignition. Idling operation causes an increase in high emissions formation and fuel residue in the exhaust (Rahman *et al*., 2013; Rahman *et al*., 2014). The amount of fuel wasted also varies with the engine size and vehicle size; bigger engine and bigger vehicle have higher fuel wasted (Curran *et al*., 2013; U. S. Department of Energy, 2011).

Current engine-driven compressor requires the vehicle's engine to be turned on to operate the compressor even when idling. To minimize the time of engine idling, the compressor need to be independent from the engine crankshaft so that the on/off engine technology could be more efficient. The need to use the electric compressor is so important to increase the mileage of the vehicle can go at various driving conditions. Vehicles idling causes waste of fuel and increase greenhouse gases to the environment (Natural Resources Canada, 2013; National Inventory Report, 2008; Gordon and Taylor, 2003).

This research work aims at analyzing the performance of retrofitted electric DC compressor into conventional internal combustion petrol engine vehicle air conditioning system with VSC to vary the compressor speed operation for different thermal load and temperature setting. The stress is on reducing the fuel consumption of the vehicle using VSC via FLC to control the speed of compressor matching cooling capacity with the cooling load to obtain linear temperature based on temperature setting inside vehicle compartment.

1.3 Objectives

The objectives of this research are given as follows:

a) To analyze two-point cabin air temperature average, COP and fuel consumption of belt-driven compressor with On/Off control, DC compressor with On/Off control and DC compressor with Fuzzy Logic control.

b) To determine fuzzy logic rule for optimum energy consumption.

c) To propose a variable capacity control strategy for an automobile air conditioning system using an electric compressor with implementation of fuzzy logic controller.

1.4 Scope of Research

The scopes of this research can be summarized as follows:

(i) Compact conventional internal combustion engine petrol vehicle.

(ii) Two-point average vehicle cabin temperature.

(iii) To obtain the base fuel consumption of the conventional internal combustion engine petrol vehicle at constant speed of 0, 30, 60, 90 and 110 km/h on a roller dynamometer.

(iv) To measure data of conventional engine-driven compressor vehicle air conditioning system with experimental settings :

a) Mechanical On/Off thermostat controller placed in evaporator.

b) Temperature setting: 22 and 24°C.

c) Internal heat load: 100, 200, 300 and 400 W.

d) Vehicle speed: 0, 30, 60, 90 and 110 km/h.

(v) Retrofit 12V DC compressor to a conventional engine-driven compressor vehicle air conditioning system.

(vi) To analyze the data of 12V DC compressor vehicle air conditioning system using the original engine-driven On/Off controller with experimental settings :

a) Mechanical On/Off thermostat controller placed in evaporator.

b) Temperature setting: 22 and 24°C.

c) Internal heat load: 100, 200, 300 and 400 W.

d) Vehicle speed: 0, 30, 60, 90 and 110 km/h.

(vii) Developed an embedded controller with FLC design :

a) Embedded controller.

b) Cabin temperature sensor at the centre of vehicle between front seats.

c) Closed-loop control system.

d) Two input and one output fuzzy variables. The fuzzy input variables are the error of temperature setting and cabin temperature and delta error is the rate of change of error. The fuzzy output is the PWM signal to vary voltage input to the inverter of the DC compressor.

e) Triangular type of membership function

f) Defuzzification use centroid method.

g) Refinement method for fuzzy tuning.

h) 3 x 3 matrix for FAM rules.

(viii) To measure data of 12V DC compressor vehicle air conditioning system using the developed FLC controller with experimental settings :

a) Temperature setting: 22 and 24°C.

b) Internal heat load: 100, 200, 300 and 400 W.

c) Vehicle speed: 0, 30, 60, 90 and 110 km/h.

(ix) Investigation and assessment for all controllers such as: the vehicle two-point average cabin air temperature, COP, fuel consumption, and fuel saving.

1.5 Project Implementation

The research begins with literature review on the internal combustion engine vehicle air conditioning system and implementation of the electric compressor which focused on the DC compressor on various applications. The original engine-driven compressor system of internal combustion engine vehicle is conducted to study the effect of various vehicle speeds to the original air conditioning system performance. The 12V DC electric compressor is then retrofit into the vehicle and experiments on the constant speed of DC compressor is conducted.

The results obtained are then used to tune fuzzy logic rules via refinement method to get the best result of fuel consumption and temperature control. A C++ coding is implemented to the embedded controller with FLC controller system used to control the VSC of the DC compressor. The embedded microcontroller is then control the voltage input to the inverter of the DC compressor and analysis of the system is conducted. The FLC is designed and tuned based on two-point average temperature at both the vehicles' front seats and energy consumption of the DC compressor. Analysis and discussion of all three systems is performed and compared. The best system is then propose to replace the existing system. This project implementation can be illustrated in a form of flow chart as shown in Figure 1.1.

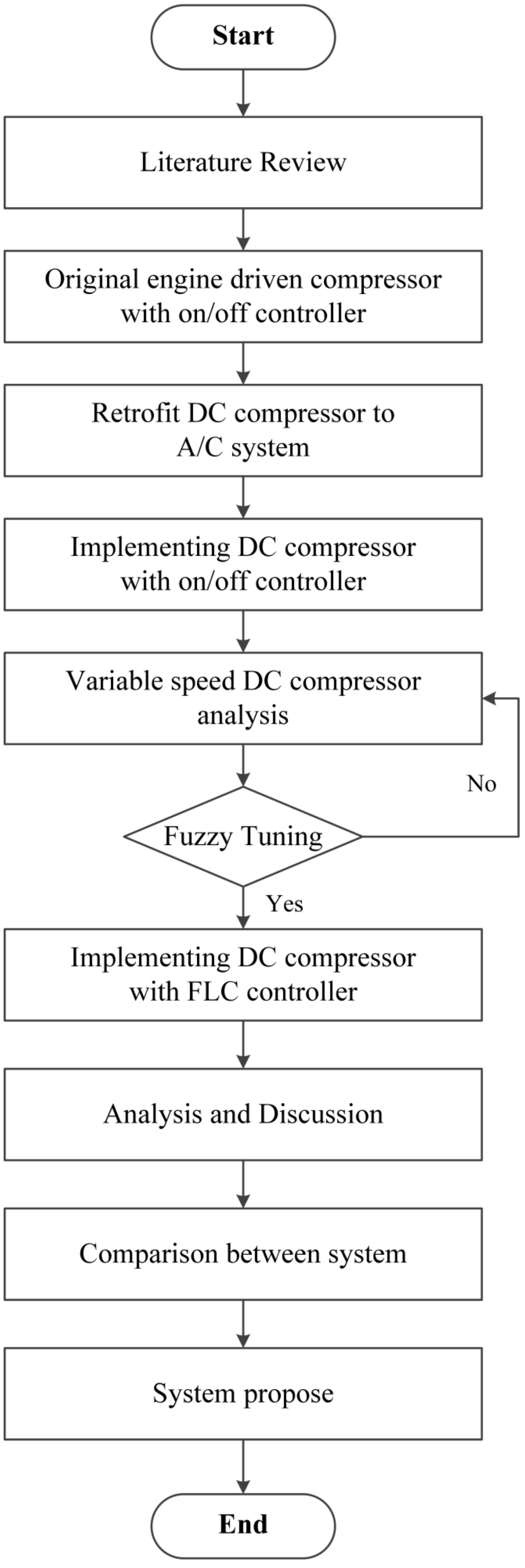

Figure 1.1 Flow chart of the project implementation

1.6 Significance of Research

The implementation of DC compressor in vehicle air conditioning offers better temperature control of vehicle compartment and by further applying VSC system, better temperature control and lower energy consumption is achieved, thus lower down the overall vehicle fuel consumption. The independent electric compressor from the engine restriction increased the efficiency of vehicle air conditioning system thus offering higher fuel saving. Implementation of this system offers further higher efficiency of the vehicle for carrying out the engine on/off system during traffic as the compressor does not turned off and longer time of engine off can be obtained, thus higher fuel saving.

1.7 Thesis Outline

This thesis consists of five chapters. Chapter 1 is the introduction of the thesis, highlighting the significance of the manuscript. The objectives and scopes of the study is also discussed in this chapter.

Chapter 2 discuss about the literature review of the study. The focus is on research and development on the vehicle air conditioning performance, the engine-driven compressor air conditioning system, electric compressor in various vehicles, variable speed control of compressor and control system for electric compressor of vehicle air conditioning system. Gaps of study are identified and the objective of the study and also methodology of the study is discussed.

Chapter 3 discuss about the experimental method and vehicle air conditioning system characteristics. The development of the system with the integrated hardware and software for on/off controller and variable compressor control system implementation to the electric compressor is discussed. A variety of instruments are needed for measurement of the system and each instrument is specified.

Chapter 4 present the results and discussion of the study. The analysis of electric consumption, fuel consumption, coefficient of performance and energy saving analysis for engine-driven compressor with on/off controller, DC compressor with on/off controller and DC compressor with VSC is made and compared with each system. The tuning of fuzzy logic rule is made to get the best temperature control in vehicle compartment.

Chapter 5 presents the conclusion of the study, contributions of this research, and recommendations for future study.

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