VARIABLE SPEED DRIVES OF RECIPROCATING COMPRESSOR FOR AIR CONDITIONING: LITERATURE *REVIEW*

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ABSTRACT

Energy conservation, which started as an action to reduce demand for energy in an individual country, has now become a subject of regional and even worldwide discussion. It is not only applied on a new design system but also on retrofit projects. As long as they fulfill the condition of energy saving, that is having the lowest or minimum energy consumption while satisfying the user's needs. One sector where the energy consumption is rising steadily is in the air conditioner system. An air conditioning system uses a lot of energy, mostly for the compressor as the heart of the system. Since energy consumed by a compressor in an air conditioning system is the highest compared to other component it is naturally wise to consider the energy saving in the compressor. The potential of variable speed control of compressor for providing load matching capability has become an interest in the efforts to reduce the energy consumed by the compressor. Control system very important in air conditioning system when the system is designed to operate automatically. These control methods may utilize differences between space and set point values of temperatures, subsequently, to control motor speeds.

Key words: Variable speed, control system, reciprocating compressor, air conditioning, save energy.

Introduction

Energy shortages has become more severe with each passing year. The cost of fuels and electricity, with the possibility of not having enough energy at any cost, is a real problem for a country like Malaysia, which is now going towards an industrialized country and hence will definitely require high energy consumption.

Electric energy is one of the essential energy source that has been drastically increased in cost since 1973. In Malaysia, the demand on

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electric energy is increases each year with average rate of 11.2 % per annum, parallel to the development of technology in this country. The consumption of electricity include the application of lighting, electrical appliance, machineries, and also air conditioning system (Norlidah, 1995).

The demand for electricity in Malaysia is influenced by many factors, including population growth, per capita income, demographic changes such as increasing urbanization and economic growth. The economic turmoil in 1997 forced the Malaysian government to postpone the development of the 2400 MW Bakun electricity generation project. Since then policy makers have taken many steps to replant the electricity consumption and distribution. One of the actions is to develop a minimum energy efficiency standard for room air conditioners, which will be implemented sometime in the future (Masjuki et al., 2001 ; Mahlia et al, 2002).

Air conditioner system for buildings are a major consumer of electrical energy. The electric power consumption of a compressor accounts for about 90 % of the total electric power consumption of an air conditioner (Tojo, et al., 1984). The number of room air conditioners has increase from 13251 units in 1970 to 253 399 in 1991, and will about 1 511 276 in the year 2020 (Masjuki et al., 2001).

These improvement have not required dramatic changes in product design nor the use of unusual basic technology. Neither has refrigerator energy performance so far reached any fundamental technological limits. There remain considerable improvements that can be made. Technological option to improve energy efficiency in refrigeration such as : improved compressor efficiency, variable and rated speed compressor, alternative refrigerant, variable speed van, superior fluid control system, etc. (OECD, 1997).

Many domestic electrical appliances with an inverter system has come into use. The inverter system is a device which converts a commercial alternating current into one with adjustable frequency and voltage. The inverter system is also used in air conditioning systems to adjust the mean speed of compressor driven by the induction motor, and thus an air conditioning system with variable speed compressor is formed. The use of speed variation of motor driving compressor of air conditioning system to control environmental temperature will be investigated by this research.

Control systems very important in air conditioning system when the system is designed to operate automatically. These control methods may utilize differences between space and set point values of temperatures, subsequently, to control motor speeds. This new concept of controller maintains the simplicity and wide applicability and use acquired knowledge to improve the performance of the control system.

Energy Consumption and Energy Conservation

Energy consumption in most developing countries always increase significantly every year due to the development they are accomplishing. The more developed the country is the more energy it consumes. High energy consumption poses many problems to a country, high fuel costs are obvious while energy shortage may become a problem in a short or ling term. Environmental problems should also be considered.

The energy consumption for air conditioning system is highest compared to other system such as lighting, elevators, escalators and others. Figure 1. show it consumed about 72 % of energy for mechanical and electrical equipment (Norlidah, 1995). Masjuki (2001) reported of estimated annual energy consumption based on *Business as Usual* (BAU) and *Standard* (STD) for air conditioning (Figure 2.).

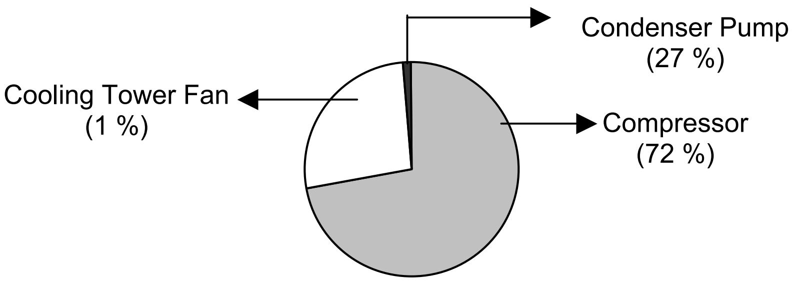

Figure 1. Typical energy consumption in air conditioning

Energy conservation can be loosely defined as the efficient use of energy at the same level of satisfaction for consumer. The term at the same level of satisfaction for consumer's is quite important since there are actually many simple ways to save energy but unfortunately they often sacrifice people's satisfaction.

Energy conservation is very flexible since it can be applied successfully not only for a new design but also for an old one. Hence old equipment can be retrofitted in order to conserve energy. It is obviously true that retrofitting itself needs costs as well, this always hinders users to apply energy conservation, afraid of high cost they have to spend. However, in most practical cases the savings in energy cost are much higher compared to the costs spent for the retrofitting. Economic analysis should be carried out to determine the feasibility on an energy conservation project.

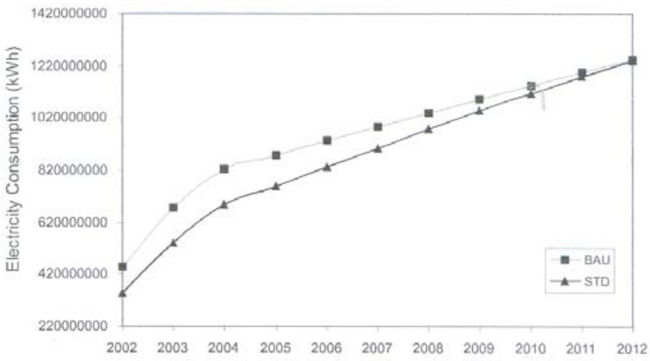

Figure 2. Energy consumption (BAU & STD) for room air conditioner

The National Appliance Energy Conservation Act (NAECA) of 1987 establish minimum energy efficiency standards for room air conditioners, which became effective on January 1990. The 1990 minimum energy efficiency ratios (EER) range from 8.0 to 9.0 (Btu/h)/W (2.34 to 2.64 W/W). Methods for improving the efficiency of room air conditioner are : *increase frontal heat exchanger area, increase depth of heat exchanger, increase fin density, add sub cooler to condenser coil, improve fin design, improve tube design, spray condensate onto condenser coil, improve fan motor efficiency, improve compressor efficiency, design options for improving seasonal efficiency and alternative refrigerant* (Rosenquist, 1998).

In order to determine the payback period and life cycle cost of the various design option analyzed, it was necessary to determine their annual energy consumption (Rosenquist, 1998). Thus,

$$AEC = \frac{\text{Capacity}}{EER}.\text{Hours}.0.001 \qquad (1)$$

where : AEC (annual energy consumption – kWh/year), Capacity (cooling capacity – Btu/h), EER (energy efficiency ratio – [Btu/h]/W), Hours (hours of compressor operation – 750 hours/year), 0.001 (conversion factor – kW/W).

Variable Speed Drives

In regulating the speed, the frequency converter is used. Inverter based variable speed drive technology is presently well proven in various applications throughout all sectors of industry and several drive types are available for both energy conservation and high performance. A three phase variable speed drive (Qureshi, 1996), shown in Figure 3.

Application of variable speed capacity control to refrigeration systems has been under consideration for the last 20 years. In variable speed systems step less speed variation is achieved by electronic variable speed drives at motor (Rosenquist, 1998 ; Rieger, 1988 ; Lloyd, 1982 ; Krueger, 1994). A three phase variable speed drive consists of a rectifier which converts the three phase main voltage i.e. 415 V, 50 Hz to DC voltage and an inverter which inverts the DC voltage to AC supply voltage to the compressor motor which adjustable in magnitude and frequency. There are different types of electronic variable speed drives which can be broadly classified into : *six – step voltage inverter (VSI), six – step current inverter (CSI)* and *pulse – width modulated source inverter (PWM)*, (Tassuo, 1998 ; Miller, 1988). Theoretical comparison of various capacity control methods at full and part load conditions in Figure 4., shows variable speed as being the most energy efficient technique (Qureshi, 1996).

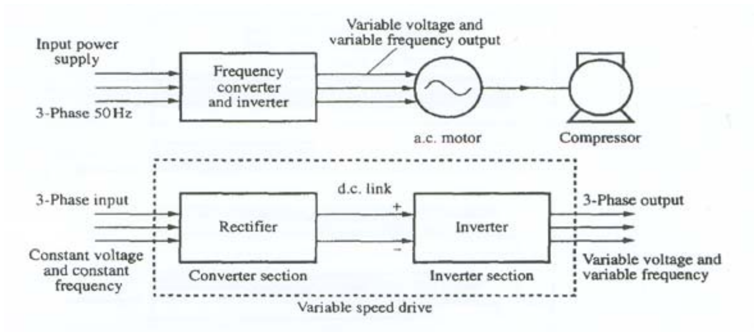

Figure 3. Basic configuration of electronic variable speed drive

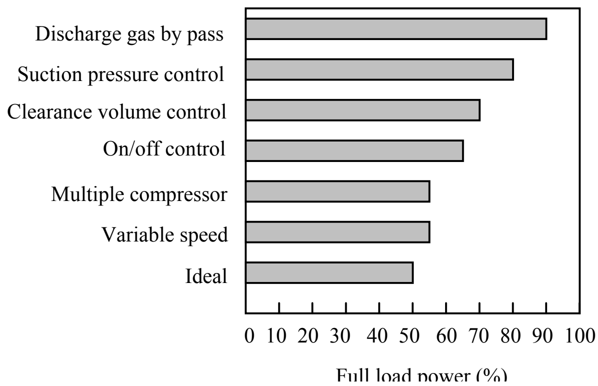

Figure 4. Comparison of various capacity control techniques at half load

Cawley *et al.* (1974) compared the part load efficiency of two speed compressors with compressor unloading capacity control. It was found that 49 % better energy efficiency ratio (EER) could be realized by a system with a two speed compressor, compared with a system using cylinder unloaded compressor. The basic reason stated for this improvement was decreased power input requirements in the two speed compressor, due to lower frictional losses at half speed.

Lloyd (1982), analysis of two widely used waveforms, six step and pulse width modulated (PWM), compared to a pure sinusoidal waveform. A standard production three phase 3 kW compressor motor was dynamometer tested using a variable frequency motor generator set, a six step silicon controlled rectifier (SCR) inverter, and a PWM power transistor inverter. The intention of this study is to show how the various waveform affect the efficiency of the motors, neglecting the inverter losses, and how they affect the out put and efficiency of the compressor. Varying the power supply frequency to the motor of a compressor is an excellent way of modulating its output. If a sinusoidal waveform is used, the efficiency of the compressor can be kept high, while the output is varied over a wide range. In this study the J/s.W (Btu/w) was reduced only 5 % and the output was reduced 55 %.

Lida *et al.* (1982) carried out experimental investigations on a heat pump equipped with a 4 hp, (3 kW), hermetic rotary compressor. It was found that the practical limits for compressor speed variation were between 25 and 75 Hz. The result indicated improvements in EER with the inverter driven compressor, compared to a fixed capacity system. The reason stated for the improvement was higher efficiency at part load, which reduced the power consumption and cycling losses. Cost and EER analysis showed a 20 % increase in the total cost for the inverter controlled system and between 20 and 26 % energy saving over the single capacity system.

Miller (1988), compared the adjustable speed drives a six step voltage source inverter (VSI), a pulse-width modulated inverter (PWMI) and an motor generator. The reciprocating compressor is hermetically sealed and has a rated capacity of 36.5 Kbtu/h (10.7 kW). The compressor has dual pistons, and the total piston displacement is 3.64 in^3 (59.6 cm^3). The 2.75 hp (2 kW) compressor motor is a two pole, three phase, three wire induction motor with y - connected stator winding. The compressor was designed to operate in the heating mode from 15 through 90 Hz line frequency (855 to 5130 rpm), in the cooling mode limited to 60 Hz (3420 rpm). A constant sinusoidal/frequency ratio was seen to be optimal for compressor drive frequencies of 60 through 15 Hz in both heating and cooling modes at fixed outdoor air temperatures. The optimal sinusoidal/frequency control for the variable speed indoor blower motor was varied with speed and was different from the constant sinusoidal/frequency control observed for the compressor because, for fan applications, as speed decreases by roughly the torque decreases by roughly the square of speed. Compressor efficiency losses due to the pulse-width modulated inverter and voltage source inverter drives increased as speed decreased because of the effect of current harmonics on the induction motor. Results indicated that direct inverter current were dominant for blower applications, indirect motor losses due to harmonic currents were dominant for compressor application.

Riegger (1988) investigated the potential of a variable speed compressor for enhancing the performance of heat pump systems. A variable speed compressor has the potential of delivering the load matching performance required for a residential heat pump/air conditioning system over a wide range of ambient operating temperatures. Typical performance compressor types air conditioning/heat applications :

Rotary	CAP 5 – 20,000 Btu/h
Reciprocating	EER 8 – 11 Btu/Wh CAP 5 – 15,000 Btu/h
	EER 8 – 9.5 Btu/Wh
	CAP > 15,000 Btu/h EER 9 – 11 Btu/Wh
Scroll	CAP 35 – 75,000 Btu/h EER 9.5 – 11 Btu/Wh

Figure 5. Typical performance compressor types air conditioner/heat application

Garstang (1990), the air conditioning variable frequency inverter has made practical variable speed compressor reality. This technology has developed so quickly for the refrigeration industry that many of the people involved in engineering, sales and service are not familiar enough with the terminology, benefits, and system design changes required for a variable speed refrigeration system.

Takebayashi, *et al.*(1994), have studied : Compressor for household air conditioners are operated under various conditions. Especially for small capacity household air conditioners, compressors must operate at a wide range of speeds. In addition, for low speed operation, the compression ratio is usually low and the operating time is long, so it is important to improve the performance of these compressors.

Norlida (1995) investigates energy saving through retrofitting of the compressor motor in an air conditioning system. Comparing energy consumption data from the constant speed compressor and variable speed drive (after retrofitting), it is found that the retrofit yields energy saving between 26,1 and 33.7 %.

Tassou *et al.* (1998), the research work aimed at quantifying the performance of compressors and drives under variable loading conditions. Emphasis is placed on the performance of three alternative compressor technologies (Rotary vane, a semi hermetic reciprocating and an open type reciprocating compressor) driven by a Pulse Width Modulated (PWM) inverter. The overall aim of the work is to identify and develop design and control criteria for the optimum integration of compressor and variable speed drives for refrigeration applications. From the compressors tested, the open type reciprocating compressor configuration is the most suitable for variable speed operation. This compressor showed an improvement in the COP during low speed operation for both constant and variable head pressure control. The rotary vane and semi hermetic reciprocating compressor showed no improvement in the COP at low speed for constant head pressure operation. However, both compressors exhibited a significant increase in the COP at low speed under floating head pressure control. The energy analysis carried out showed the losses of the pulse width modulated inverter based variable speed drive used in the investigations to be around 5 %. It has also been shown that irrespective of the type of compressor used, variable speed refrigeration systems based on pulse width modulated inverters and standard induction motors can provide higher seasonal efficiencies compared with fixed speed refrigeration systems in air conditioning applications. The utilization of variable speed refrigeration systems for air conditioning applications will be more cost effective in warm climates due to longer operating hours of the system during the cooling season. The efficiency of variable speed refrigeration systems can be improved further through the use of high efficiency motors and better control and integration of system components.

Park *et al.* (2001) carried out experiment the system performance variations with cooling load in an inverter air conditioner with electric expansion valve and with the load ratio of each evaporator of the multi type inverter air conditioning system. In an inverter air conditioner with electric expansion valve, there are limitations of the operating frequency of the variable speed compressor to cover the given cooling load. The operating frequency selection in the inverter air conditioner should be the lowest frequency to get the highest COP within the variable range of the compressor operating frequency when the system capacity matches the imposed cooling load on the system. If the cooling load increases, the system has to increase the operating frequency because of the limitation of the cooling capacity of the system at a fixed operating frequency. Consequently, the maximum COP at an operating frequency decreases with cooling load even after adjusting the electric expansion valve opening.

Control System for Air Conditioning

Conventional air conditioning control system are run on a fixed setting throughout the day, with the target value room temperature for the building facility space. The control center of the building used to be unable to change this fixed setting even in cases in which the setting led to energy being wasted as a result of excessive heating or cooling. The principle that the target set values for the room temperature should or could be changed more finely to suit the constantly changing room environment did not exist (Yamada, 1999).

In air conditioners, various energy saving countermeasures have progressed based on recent changes in the energy environment. Regarding an evaluation method for efficiency, not only energy efficiency (EER) during rated operation, but also seasonal energy efficiency (SEER) under actual operating condition have received a considerable amount of attention. There are various types of actually utilized capacity control systems, as shown in Table 1 (Itami *et al.*, 1982).

Temperature and humidity are important parameters which must be often carefully controlled in many applications of air conditioning such as in textile, paper industries, building, etc. Conventionally, the accurate control of those parameters are accomplished by cooling the air to the required relative humidity and reheating the air to the required temperature. The use of variable speed motor to control temperature and relative humidity has been investigated by Krakow *et al.* (1995). They have developed a numerical model of an environmental control system including refrigeration, space, and PID control sub-system. Their investigation indicate that space temperature and relative humidity may be controlled simultaneously by the simultaneous operation compressor speed and evaporator fan speed respectively. However, the investigation also indicated that the two parameters are not successfully controlled using the methods suggested. Their study do not include power consumption.

Table 1. Capacity control method in small sized compressors for air conditioners.

Control Method	Features
ON/OFF Operation	Control of the capacity according to operated time. Because of the simple structures and low price this method is generally utilized in small sized air conditioning equipment. The work loss under partial load and at the time of starting is large, and the efficiency is decreased.
Cylinder unloader (2 cylinder)	Converting the number of operated cylinders according to the load. Two stage capacity control is possible, and capacity control of as much as 50% can be performed. Reduction of efficiency under partial load is small.
Twin compressors	Converting the number of operated compressors according to the load. Two stage capacity control is possible, and capacity control up to 50% can be performed. The reduction in efficiency under partial load is zero.
Gas injection	Controlling the quantity of discharged gas according to the load. Two stage capacity control is possible, but the capacity range is narrow and is between approximately 10% - 20%. The more the release is increased, the lower the efficiency becomes.
Two – Speed motor (Two – Pole Four Pole)	Converting the number of poles of the motor according to the load. Two stage capacity control is possible, and capacity control of as much as 50% is possible, but motor efficiency under partial load is decreased.
Inverter Driven	Controlling the operation frequency of the motor according to the load. Stepless capacity control over optional ranges is possible, and optimum capacity control can be performed.

There are not many papers at present which discussed the possibility of conserving energy using the application of variable speed control of reciprocating compressor for air conditioning. Table 2., shows the available research of control system for air conditioning from 1982 to 2002.

Table 2. Research of control system for air conditioning

No.	Years	Author	Title	Objective	Explanation	Controller
1	1982	R. Schuman	Digital Parameter adaptive control of an air conditioning plant	Adjustable speed	Fan	DDC
2		J.D. Lloyd	ıriable speed compressor motors erated on inverter	Adjustable speed	Compressor	Manual

No.	Years	Author	Title	Objective	Explanation	Controller
3	1984	C.G. Nesler & W.F.Stoecker	Selecting the proportional and integral constants in the DDC of discharge air temperature	Supply air flow	Valve and Damper	PI
4	1985	CC Lim & CC Hang	Air conditioning & Ventilating control using industrial process control strategy	Supply air flow	Damper	P & PI
5	1986	C.G.Nesler	Automated controller tuning for HVAC applications	Supply air flow	Damper	PI
6	988	).K. Riegger	ariable speed compressor rformance	Adjustable speed	Compressor	Manual
7		V.A. Millier	boratory efficiency comparisons of odulating heat pump components ing adjustable speed drives	Adjustable speed	Compressor & Blower	Manual
8		I. Ishii *et al.*	n the superior dynamic behavior of a riable rotating speed scroll mpressor	Adjustable speed	Compressor	Manual
9	990	I. Ishii *et al.*	echanical efficiency of a variable eed scroll compressor	Adjustable speed	Compressor	Manual
10	1990	T. Hirano & T.Shigeoka	The scroll compressor with variable capacity control mechanism for automotive air conditioning	Variable capacity	Valve	Manual
11		S.W. Garstang	Variable frequency speed control of refrigeration compressor – Part.1	News	General	General
12	1991	S. Huang & R.M.Nelson	A PID – law – combining fuzzy controller for HVAC apllications	Simulation process HVAC	Process HVAC	PID, Fuzzy
13	1993	W.F. Ho	Development and evaluation of a software package for self tuning of three term DDC controller	Simulation (self tuning PID program)	Valve, room, cooling coil.	PID DDC
14	1994	I. Takebayasl *et al.*	rformance improvement of variable eed controlled scroll compressor for usehold air conditioners	djustable spe	Compressor	Manual
15		S. Huang & R.M.Nelson	Rule development and adjustment strategies of a fuzzy logic controller for an HVAC system : Analysis	Development of rule based FL	HVAC	Fuzzy
16		S. Huang & R.M.Nelson	Rule development and adjustment strategies of a fuzzy logic controller for an HVAC system : Experiment	Supply air flow	Damper	PID, Fuzzy
17		S. Huang & R.M.Nelson	Delay time determination using an artificial neural network	Supply air flow	Damper	NN
18		K.V.Ling & A.L.Dexter	Expert control of air conditioning plan	Supply air flow	Damper	Fuzzy, Predictive
19	1995	K.I. Krakow *e al.*	mperature and humidity control duri oling and dehumidifying by mpressor and evaporator fan speed riation	umerical mod for adjustable speed	Compressor & Evaporator Fan	PID
20	1996	T.Q.Qureshi & S.A.Tassao	Variable speed capacity control in refrigeration	Review paper	General	General
21	1997	W.Huang & H.N.Lam	Using GA to optimize controller parameters for HVAC	Simulation of heating	Boiler	PI
22	1998	W.Chen *et al.*	Membership function optimization of fuzzy control based on GA	Simulation performance	Evaporator	Fuzzy
23		Y. Kim *et al.*	odeling on the performance of an verter driven scroll compressor	umerical mod for adjustable speed	Compressor	Manual
24		S.A. Tassuo & T.Q.Qureshi	omparative performance evaluation o sitive displacement compressors in riable speed refrigeration application	djustable spe	Compressor	Manual
25		E. Jeannette *et al.*	Experimental results of predictive Neural Network HVAC controller	Hot Water	Boiler	PID, NN
26		B.A.Rock & C.T.Wu	Performance of fixed, air side economizer and NN demand controlled ventilation in CAV system	Supply air flow	Fan	NN
27	1999	F. Yamada *et al.*	Development of air conditioning control algorithm for building energy saving	Online monitoring energy	AC system	Fuzzy, NN
28	1999	J. Ho *et al.*	An application of fuzzy logic to control the refrigerant distribution for the multi type air conditioner	Adjustable refrigerant	Linear expansion valve. Evaporator	Fuzzy
29		T.I. Salsbury	A practical algorithm for diagnosing control loop problem	Simulation of supply air flow	Damper	PI
30		O.S. Hernandez *et al.*	Implementation of a fuzzy logic expansion valve control for small refrigeration systems	System air conditioner	Expansion Valve	PD,ID,PID, Fuzzy
31	2001	R.N.N Koury *et al.*	umerical simulation of variable speed frigeration system	djustable spe	Compressor	On-off

No.	Years	Author	Title	Objective	Explanation	Controller
32	2001	Y.C. Park *et al.*	Performance analysis on a multi type inverter air conditioner	Variable capacity	Expansion valve	Manual
33	2002	S. Deng	The application of feed-forward control in a direct expansion (DX) air conditioning plant	Variable capacity	Thermostat expansion valve. Evaporator	Feed-forward

From 1982 to 2002, only 10 papers related to this research. Two papers present adjustable speed of compressor for air conditioning using control system such as PID control (Krakow *et al.* , 1995) and On – Off control (Koury *et al*., 2001) with numerical or simulation methods. In another papers only with manual (not used the control system) adjustable speed control of compressor. There are not many research of this topic because long time delay for setting of control system , different equipment model then also different setting of control system, and must be additional equipment such as inverter and controller for old equipment (this case must be additional cost). If we refer to minimum energy efficiency for air conditioning, energy crisis (specifically for fuel energy), if not available renewable energy, this problem must be done. Many country such as Australia, Brazil, Canada, China, Europe, Japan, Korea, Mexico, Philippine, Russia and US to start minimum energy efficiency standards for appliances have been enacted. This programs can be mandatory (i.e., government law or regulation) or voluntary (i.e., agreement with manufacturers) [Masjuki, 2001].

Concluding Remarks

The application of variable speed control to air conditioning offers the potential for substantial energy savings or energy efficiency. In variable speed control application, the compressor speed influences various operating and design parameters such as cooling load, power consumption, COP, volumetric and isentropic efficiency. Variable speed control indicate that space temperature may be controlled simultaneously by the simultaneous operation of compressor speed, with the result that operation of compressor speed to adapted of temperature (cooling load) changing. In this system is one of the actions to develop minimum energy efficiency for renewable energy.

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