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POTENTIAL OF A VARIABLE SPEED COMPRESSOR IN ACHIEVING EFFICIENT AND GREEN TRAIN AIR-CONDITIONING SYSTEM

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ABSTRACT

The potential of a variable speed compressor running with a controller to provide enhanced load-matching capability, energy saving and thermal comfort for application in the train air conditioning system is demonstrated. This paper presents an algorithm developed based on fuzzy logic control (FLC) and programmable logic control (PLC), which allows selected compressors to run at the appropriate operating speed. The main objective of the experimental work is to evaluate the energy saving obtained when the FLC and PLC algorithm, through an inverter, continuously regulates the compressor speed. It demonstrates better control of the compressor operation in terms of energy consumption as compared to the control by using a thermostat imposing on/off cycles on the compressor at the nominal frequency of 50 Hz. The experiments were conducted with temperature set-points of the conditioned space of 22^{o}C. Measurements were taken at a time interval of one minute. The experimental results indicate that the proposed technique can save energy and improve indoor comfort significantly for train air conditioning systems compared to the conventional (on/off) control technique. The experimental results also showed that more energy saving can be obtained through the use of FLC when compared to the PLC and on/off control.

Keywords: train air conditioning, variable speed compressor, energy saving, fuzzy logic control.

INTRODUCTION

In most train compartments, air-conditioning systems are installed to provide a thermally comfortable environment. However, energy consumption of the air-conditioned (AC) train compartments is large [1], which is proving an increasing problem. Almost 70% of the total energy is consumed by air-conditioning units in a train [2,3]. At the same time, rising comfort expectations show the train compartments in a worsening light [4], in view of large fluctuation in indoor air temperature experienced, due to the change of ambient conditions during a long distance travel. Therefore, serious energy consumption and thermal discomfort in the air-conditioned train compartment are becoming main challenges to the future development of railway transport in Malaysia. Thermal comfort is an important concern for the occupants of an enclosed environment [5] such as a passenger compartment. However, several factors hamper the achievement of occupant thermal comfort that is the tendency to use more glass in train styling, tightening fuel-economy constraints, the need to switch to environmentally safe refrigerants, and reduced condenser air flow. Therefore, reducing the heat loads that enter passenger compartments has become an important issue in the early stages of train AC design. It becomes necessary to develop tools that can predict the impact of various design choices on passenger thermal comfort early in the design process [6].

Standards of thermal comfort are required to help train designer provides a passenger compartment climate that train occupants find thermally comfortable. A good passenger compartment climate is important not only because it will make passengers fed comfortable, but also because it affects energy consumption and thus influence its sustainability. The energy required for climate control is an obvious target for potential reduction of energy consumption [7]. The concept of AC has developed from a conventional single speed AC system to that of a variable speed system. A variable speed AC system could distribute conditioned air at different temperatures. The system with variable speed compressors (VSC) can control the cabin temperature by changing the frequency of the motor that drives the compressor [8]. Designing a continuously controlled refrigeration system for variable speed compressor requires the designer to know how the speed of the compressor will influence the performance of the refrigeration system. There is a common question as to what type of compressor mechanism is most suitable, and what are the problems that impede its implementation [9-12]. The basic difference between variable speed direct current compressor refrigeration system and on/off compressor refrigeration system is in the control of the system capacity. In variable speed compressor refrigeration system, it is matched to the load by regulating the speed of the compressor motor in such a way that the capacity of the system tracks the load dictated to it by varying operating conditions. Differ with on/off controller which working at ±1.0°C from the desired temperature, at constant speed without considering the thermal load inside the system, causing poorer thermal comfort to the passengers. The goal of controlling a refrigeration system is to ensure that a desired temperature is achieved, and in some applications, the relative humidity as well. As a result, one would expect considerable energy savings and cost reductions. Various conventional and intelligent strategies have been used for refrigeration system control in the literature. A number of controllers have been developed so far to improve the energy efficiency associated with operating the train AC system. These controllers include: PID controller [7,13,14], rule based [15] and fuzzy controller [16-20]. The classical PID controller is still the most widely used because they have simple structures, can be designed easily and offers good control system performance at acceptable cost. Nasution and Hassan [21] show the potential of variable-speed compressor running on a controller to provide enhanced load-matching capability, energy saving and thermal comfort for application in AC system using PID controller. The results indicate that thermal comfort of the room together with energy saving can be obtained through a proper selection of proportional (P), integral (I) and derivative (D) gain for the controller. However, it is very difficult to design for nonlinear and complex systems. Regarding nonlinear and complex systems, fuzzy logic controllers have the capability to address the inherent nonlinearity of AC components and to allow the control to be expressed in the same heuristic terms that an occupant would use in describing the level of comfort [22]. As reported in the literature, fuzzy logic has been a popular method for controlling the operation of AC [16-20].

In this work, an innovative train AC system using variable speed compressor control has been proposed to overcome the shortcomings of the existing system. The main advantages of the concept are its simple installation together with the potential to conserve energy. This paper focuses on energy saving using a fuzzy logic controller (FLC) and programmable logic control (PLC). The main idea of designing the controller is to maximize energy saving for an AC system application through variable speed drive control. The results of the FLC will be compared to the on/off and PLC control.

Controllers algorithm and system performance

On/Off controller

In the field of control system, on/off control or thermostat control is generally the simplest in terms of hardware requirements. This class of controller has only two fixed states rather than a continuous output. The fixed states are, in many cases, simply on and off. In its wider application, the states of a thermostat controller may not be simply on and off, however, could represent any two values of a control variable [23]. The thermostat control process can be started by execution the decision (If-Then) statement. The thermostat system has two-decision statements that are:

- If the cabin temperature ≤ reference temperature Then the AC Off
- If the cabin temperature ≥ reference temperature Then the AC On

The statements 1 and 2 are defined as the respective upper and lower limit temperature setting, as follows:

- Lower limit temperature ≤ Temperature setting.
- Upper limit temperature ≥ Temperature setting + 1°C.

Programmable Logic Control (PLC)

A PLC is a microprocessor-based control system, designed for automation process in industrial environments. It uses a programmable memory for the internal storage of user-orientated instructions for implementing specific functions such as arithmetic, counting, logic, sequencing, and timing. A PLC can be programmed to sense, activate, and control industrial equipment and, therefore, incorporates a number of input/output (I/O) points, which allow electrical signals to be interfaced. Input device and output device of the process are connected to the PLC and the control program is entered into the PLC memory [23]. The PLC architecture is shown in Figure-1.

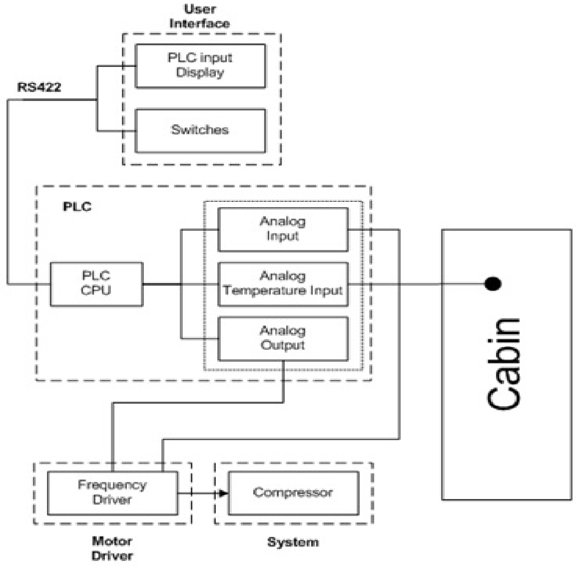

Figure-1. Control action of a PLC.

The proportional-derivative-integral (PID) PLC controller used in the study is manufactured by Mitsubishi and performs the following operations:

- Reads the sensor's data through its analogue input channels.
- Run the PID decision support algorithm for variable speed compressor.
- Drives the inverter through its digital and analogue outputs.
- Communicates with the user interface using an RS422 connection.

PLC programming is based on the logic demands of input devices and the programs implemented are predominantly logical rather than numerical computation algorithms. The programming method used is the ladder diagram method, converted into binary instruction codes so that they can be stored in random-access memory (RAM) or erasable programmable read-only memory (EPROM) [24].

Fuzzy logic control

Fuzzy logic control (FLC) has become an important approach to designing nonlinear controllers because of its simplicity, ease of design in the implementation using commercially available programming tools [25]. The control of knowledge based systems using linguistic variables that do not have precise values is of concern, and this allows the use of traditional human heuristic and experience in designing the system [26]. The method provides a man-machine interface that facilitates the acceptance, validation and transparency of the control algorithm and it has some advantages over many other approaches when the system description requires certain human experience. The FLC is based on three principal phases: fuzzification, inference mechanism and defuzzification. The fuzzification process allows the transformation of a defined value into a fuzzy value, the inference process determines the output fuzzy by means of the rules fixed according to the actual experiment and the defuzzification process permits the transformation of the fuzzy output into a defined value [27]. Figure-2 shows the block diagram of the FLC process for the cabin temperature. In particular, the figure shows a two-input and one-output FLC. The input variable is temperature error (*e*) which is the error between the reference and the measured temperature and the error difference and temperature rate-of-change-of-error (Δe) which is the rate of change of the error can be approximated as the difference between the present error and the previous error, the fuzzy output variable is the frequency of the supply current of the compressor electric motor (ΔZ).

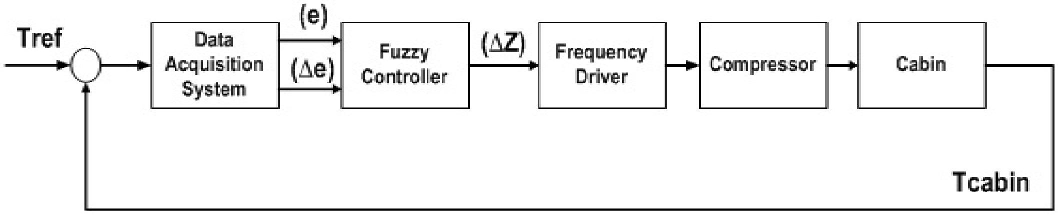

Figure-2. FLC algorithm block diagram.

Table-1 shows the rules fixed to set the algorithm and the three fuzzy subsets used to characterized the input and output linguistic variables marked with the following labels: hot (H), normal (N), cool (C), negative (NE), normal (NO), positive (PO), slow (SL), normal (NM) and fast (FT). The membership function used in this study is the triangular type. As for (*e*) and (Δe) the range covered is between –2ºC to +2ºC. As for ΔZ, a range between 0 to 5 V_{dc} is covered. The adopted defuzzification method is based on the determination of the center of gravity or centroid. In particular, this algorithm provides as an output variable a voltage signal which can be continuously used with an inverter to control the compressor speed.

Table-1. Fuzzy rules for compressor speed.

ΔZ		***e***		
		H	**N**	**C**
Δe	NE	SL	SL	SL
	NO	SL	SL	SL
	PO	FT	NM	SL

The COP of a refrigeration machine is the ratio of the energy removed at the evaporator (refrigerating effect) to the energy supplied to the compressor. The COP follows the following general formula:

$$\text{COP} = \frac{(h_1 - h_4)}{(h_2 - h_1)} = \frac{Q_e}{W_{com}} \tag{1}$$

where h_1, h_2 (kJ/kg) are the enthalpy at the compressor inlet and outlet respectively, h_4 (kJ/kg) is the enthalpy at the evaporator inlet, Q_e (kJ/kg) is the refrigerating effect, W_{com} (kJ/kg) is the compression work.

Energy calculation

Energy consumption was calculated from the start of the motor multiplied by the time of operation. The energy saving calculated is expressed in terms of saving in percentage unit, based on the difference between energy consumed using on/off, PLC and energy consumed using FLC. The equation is given as:

$$\text{Energy Saving} = \frac{\text{(on/off energy) - (PLC energy)}}{\text{(on/off energy)}} \times 100 \tag{2}$$

$$\text{Energy Saving} = \frac{\text{(PLC energy) - (FLC energy)}}{\text{(PLC energy)}} \times 100 \tag{3}$$

EXPERIMENTAL SET UP

The air conditioning unit used in the metro or railway car is a similar one in the regular building air conditioning unit. Figure-3 is the diagram of a unit, which consists of compressor, condenser, evaporator and thermal expansion valve. In order to simulate the cooling load imposed on the passenger compartment, an electric heater was immersed in the main air duct upstream to the evaporators. The evaporator inlet air temperature was attained through the use of the electric heater controller to obtain the sensible cooling load while the latent load was achieved by mixing streams of outside air with that of cooled air from the evaporator. The temperature, pressure, and mass flow rate were measured at the locations indicated in Figure-3. The refrigerant and air temperatures at various points of the system were detected by thermocouples. The thermocouples for the refrigerant temperatures were inserted inside the copper tubes. The interior surface temperatures of the simulated passenger cabin were measured by attaching five thermocouples to the interior cabin sides and nine pressures at various points of the refrigerant circuit were measured by pressure gauges. The refrigerant mass flow rate was measured using a refrigerant flow meter. The control system for the compressor speed consists of a thermocouple in the cabin, an on/off, PLC and FLC subroutine installed on a computer, an inverter and an electric motor. The thermocouple monitors the temperature of the cabin and emits electrical signals proportional to the state of the conditioned space. The output signal is supplied to the controller and computer, which send out a control signal that is a function of the error between the value of the monitored temperature and the required set point temperature. The control signal output is supplied to the inverter, which modulates the electrical frequency supplied to the motor such that it is linearly proportional to the control signal. The inverter converts the constant voltage and frequency of a three-phase power supply into a direct voltage and then converts this direct voltage into a new three-phase power supply with variable voltage and frequency. The experiments were conducted for four different conditions: variable speed, on/off, PLC and FLC controllers with 22ºC temperature setting.

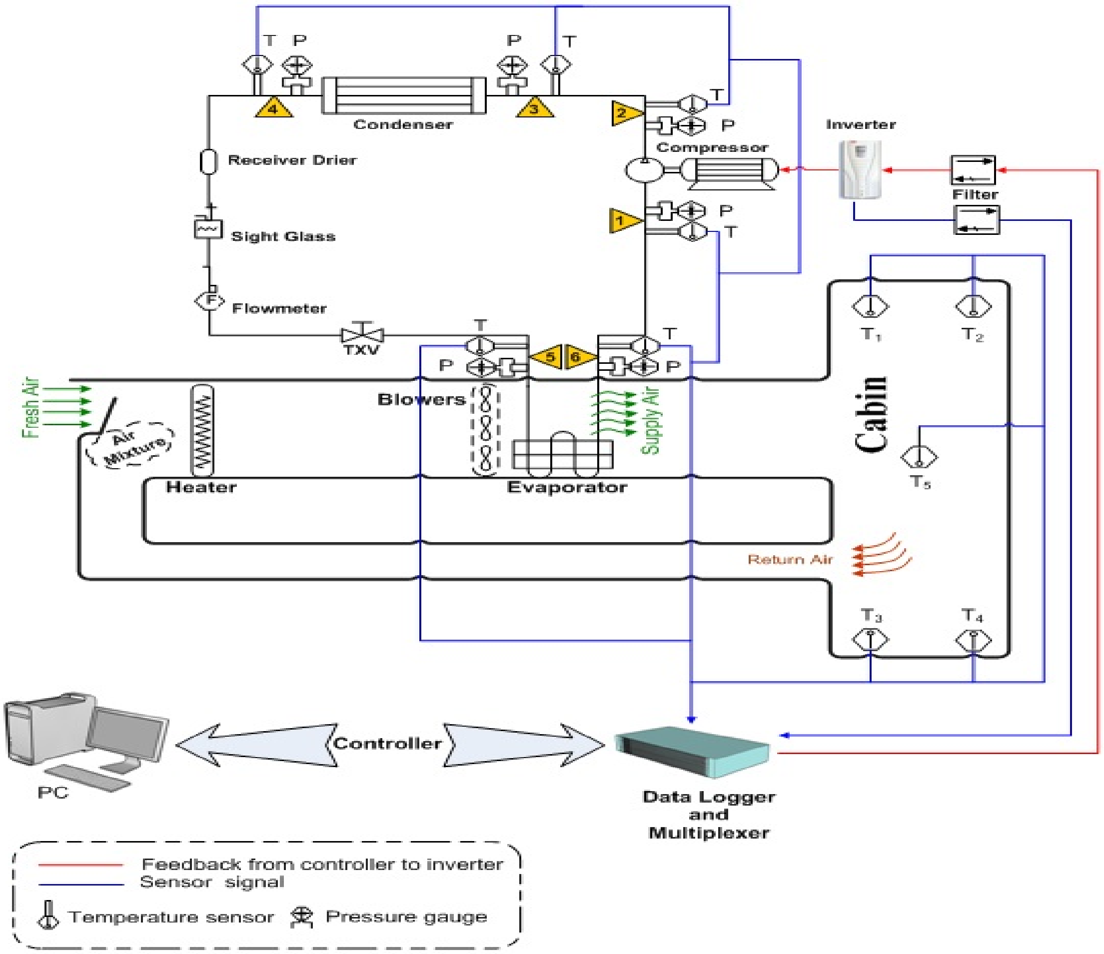

Figure-3. Schematic diagram of the experimental.

RESULTS AND DISCUSSIONS

Steady state values of cabin temperature and energy consumption at various frequencies for a test period of one hour is shown in Figure-4. From the figure, energy consumption is dependent on the motor frequency. As the frequency increases, the energy consumption increases as the compressor power consumption increases. Cabin temperature also decreases as motor frequency increases.

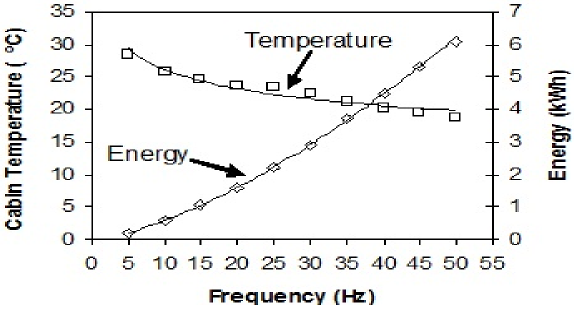

Figure-4. Steady state cabin temperature and energy consumption at various frequencies.

Figure-5 shows the cabin temperature responses against time interval using on/off, PLC and FLC controllers. On/off controller turns on the motor when the cabin temperature reaches the upper limit temperature setting and turns off at the lower limit temperature setting. The cooling load increases and thus temperature in the cabin increases at a high rate, turning on of the motor is fast. This allows faster cabin cooling time until a temperature set point is attained. The motor frequency was set to run at maximum speed of 50Hz. As time increases, cabin temperature decreases and by referring to the set point temperature, the PLC and FLC controllers minimize the error between set point temperature and cabin temperature. Cooling load affects the cabin temperature and the speed of the motor which higher cooling load results in a longer time to reach the temperature setting while the motor frequency drops as the cabin temperature reaches the set point.

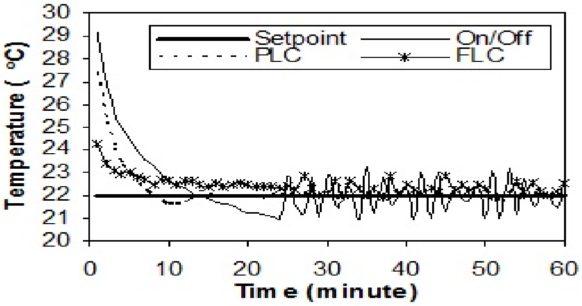

Figure-5. Cabin temperature responses.

Energy consumption of the three controllers obtained from the electrical power from the inverter between on/off control by the digital controller and the continuous compressor speed control by the PLC and FLC algorithm is shown in Figure-6. Energy consumption was calculated from the start of the motor multiplied by the time of operation. As the cabin temperature setpoint decreases, energy consumption increases because longer compressor operates at maximum speed. This resulting to smaller energy saving. Based on the power consumed between on/off, PLC and FLC, energy saving is calculated and expressed in percentage saving. Compared to on/off controller, PLC and FLC obtained energy saving of about 50.17% and 61.66%, respectively. As FLC obtained approximately 23.07 % compared to the PLC. FLC gives highest energy saving compared to on/off and PLC controller.

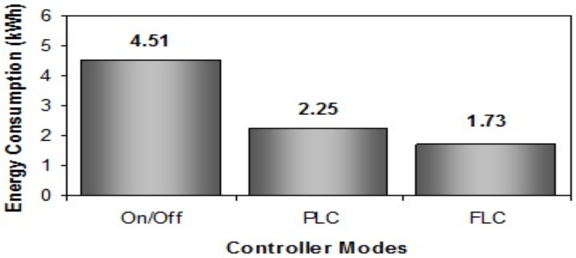

Figure-6. Energy consumption.

CONCLUSIONS

Variable speed compressor application in the train air conditioning system has been conducted experiments to study the impact of various frequencies from 5 to 50 Hz. Cabin temperatures and energy consumption is dependent directly on the frequency of the motor. As the frequency increases, the cabin temperature decreases, but higher energy consumption. This is because higher frequency requires higher compressor energy consumption. The application of variable speed controls in the train air conditioning system offers substantial energy savings for energy efficient operation. By using higher frequency at higher thermal load and low frequency at low thermal load using an inverter driven motor to control cabin temperature gives potential to achieve higher energy savings and thus lower electrical consumption with better cabin temperature control. FLC usage provides higher energy saving and better control system compared to PLC and on/off controller.

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