REDUCTION OF ENERGY CONSUMPTION IN REFRIGERATION AND AIR CONDITIONING VIA PROGRAMMABLE LOGIC CONTROLLER (PLC)

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Abstract. *This paper proposes a PLC (Programmable Logic Controller) and frequency inverter module (kit) to be applied to existing refrigeration systems to control the compressor motor speed based on a power law. The module was conceived, built in the laboratory and tested in a refrigeration chamber under a fixed thermal load. The results show that in the vapor compression refrigeration using speed control there is a reduction of energy of approximately 30% in comparison to conventional on-off control. After promising initial results, constants were further adjusted in PLC programming for several refrigerator configurations under different thermal loads using a thermal chamber in the laboratory. An electrical energy consumption economy of approximately 34% was achieved in a seven-hour duration test in comparison with the traditional on-off system, under the same operating conditions. The main conclusion is that the module could be applied to any existing refrigeration hardware with expected large energy consumption reductions.*

Keywords: *feedback control, compressor speed, intelligent refrigeration kit*

1. INTRODUCTION

The commercial refrigeration systems are based on the traditional on-off control action with limited temperature control and operation (Buzelin, 2003). The cycling continuously observed in these systems reduce the lifetime of equipment and energy consumption increases due to current peaks caused by the engine starts to drive the compressor (Li et al., 2010).

In 2001 energy consumption for heating, cooling and ventilation (HVAC & R) accounted for 30% of the total energy consumed in U.S. households (USA) and with a tendency to increase with global warming (Buzelin, 2003). A similar phenomenon occurs in Brazil and other countries, the sector having a major impact on overall energy consumption.

The need for rational use of energy is a global concern and a necessary challenge to reduce energy wastage without compromising the advantages brought by the use of energy and without affecting the efficiency and quality of facilities (Li et al., 2010; Garcia and Bandarra, 2006; Tassou and Qureshi, 1994; Tassou and Qureshi, 1997; Tassou and Qureshi, 1998).

The air-conditioning and refrigeration systems are widely used in residential, commercial and industrial facilities operating in controlled temperature environments for human comfort and storage conditions of food and other utilities. Thus, an improvement in the efficiency of cooling systems results in a substantial improvement in energy savings.

Our proposal is then no longer in the use of compressor on-off control systems, but rather changing the speed of the compressor (Parreira and Parise, 1993) according to thermal load by means of an algorithm developed previously by the authors (Vargas and Parise, 1995; Buzelin et al., 2005), and in a programmed PLC expecting to provide significant energy savings compared to the traditional on-off system.

2. MATERIALS AND METHODS

In this work we used an existing thermal chamber at Universidade Federal do Paraná, UFPR; a Bitzer condensing unit with a 3.5 kW capacity using R22 as the refrigerant; a McQuay, FBA 215 evaporator; expansion valve equalizing external TEX2, CW08; an inverter manufactured by WEG; a PLC model 10SX manufactured by Delta with 4 inputs and digital outputs and 2 analog inputs and outputs, and an expansion to PLC with Delta brand 4 digital inputs.

The experimental work involved the acquisition of the refrigeration system temperature and power consumption data in real time. This task was performed through the utilization of a computational data acquisition system which consisted of a digital multimeter board, NI PCI-4060, a NI PCI-6703 analog output board, and a SCXI-1127 32-channel high voltage multiplexer, all manufactured by National Instruments, USA, which allowed for the sequential data acquisition from 32 channels at interval times of 0.1 s. All the data were processed by a suitable software application to convert the signals into temperature and power readings.

The intelligent control kit and the refrigeration system are shown in Fig. 1, and consist of the PLC (Programmable Logic Controller) and frequency inverter module (kit) on the right, and of the refrigeration system on the left. The programming of the PLC followed the current available methodology in the literature (Silveira and Santos, 1999; Maya and Leonardi, 2010).

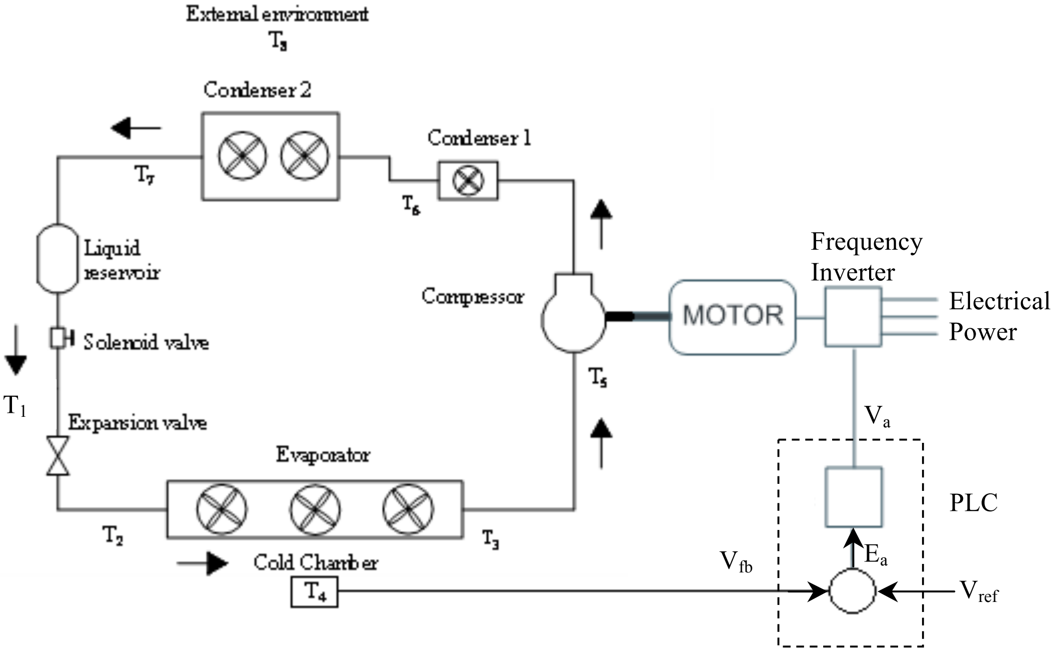

Figure 1. Diagram of the PLC and frequency inverter module (right), and of the refrigeration system (left).

3. THE CONTROLLING SYSTEM

The electronic data acquisition board reference signal varies between $V_{min} = 0$ V to $V_{max} = 10$ V. Therefore, the feedback signal generated by the thermistor circuit is given by

$$V_{fb} = f(T_4) \tag{1}$$

where $V_{min} < V_{fb} < V_{max}$, and f is the thermistor circuit nonlinear function that translates the correspondence between voltage and °C.

Considering a reference signal, V_{ref}, which corresponds to the setpoint temperature, T_{set}, the acting error is calculated by

$$E_a = V_{fb} - V_{ref} \tag{2}$$

Likewise, the closed-loop control action was based on the acting error of Eq. (2). However, the compressor speed was kept in the range of 850-1750 rpm (30-60 Hz), in order to comply with the supplier recommendation of not operating piston compressors at frequencies below 30 Hz, to avoid lubrication problems.

In order to exert the control action, the acting error, E_a, is utilized to generate the control signal to regulate compressor speed. First, the difference between the actual air temperature in the cold chamber, T_4, and the setpoint temperature, T_{set}, is determined by

$$\Delta T = f^{-1}(E_a) \tag{3}$$

The equation to calculate the adjustment signal, V_s, must identify the control action starting point. This task is performed by the following expression:

$$V_s = K_c^{(K_1 \Delta T + K_2)} + K_3 \tag{4}$$

where K_c, K_1, K_2 and K_3 are constants that have to be selected accordingly (e.g. experimentally). The control signal, which is the input of the frequency inverter, is given by

$$V_a = V_s, \ \text{if} \ \ V_s < V_{max} \tag{5}$$

and

$$V_a = V_{max}, \ \text{if} \ \ V_s \geq V_{max} \tag{6}$$

The objective of the control action defined by Eqs. (3) to (6) is two-fold: i) to ensure that V_a is less than V_{max} only when close to setpoint, and ii) to avoid undesirable temperature oscillations in the controlled ambient temperature,

T_4, after the setpoint temperature is reached. When $V_a = V_{max}$, the compressor runs at maximum speed, and when $V_a = V_s$, the compressor runs at a reduced speed regulated by the frequency inverter and the adjustment signal.

The "on-off" control was implemented using a dead band of ± 0.5°C to reactivate the system.

The main difference between the proposed system and the primary "on-off" one is that when the compressor is commanded to return to operation (i.e. measured temperature greater than setpoint), the compressor works with a speed, as controlled by the frequency inverter, equal to the minimum nominal rotation (30 Hz – 850 rpm), which is much lower than its maximum rotation and as a consequence decreasing energy consumption.

4. RESULTS AND DISCUSSION

Figure 2 shows the operation of the on-off (left) and closed loop (right) refrigeration systems. It is shown the temperature of the thermal chamber with respect to time during the tests conducted in the laboratory. With the on-off control, there was a greater variation around the set-point than with the closed loop one, due to existence of a larger dead-band, which in turn causes a high compressor cycling with high current peaks. In the closed-loop system using the inverter driven by the PLC algorithm with the power law control action, it is observed less variation around the set point than with the on-off one.

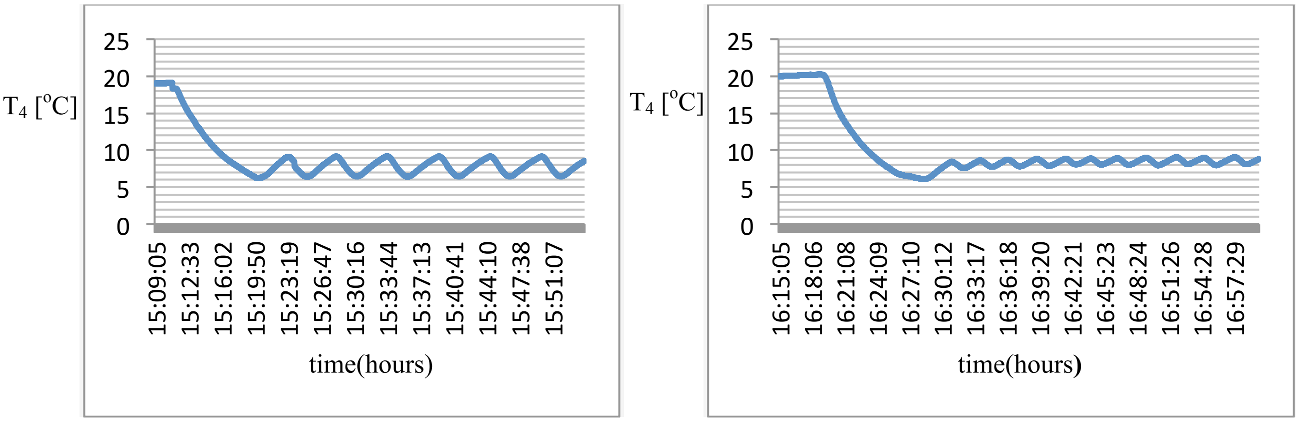

Figure 2. On-off (left) and closed loop (right) refrigeration system operation.

The results with respect to energy consumption show an approximate reduction of 34% of energy consumption with the power law control in comparison to the on-off control, as Fig. 3 demonstrates. These findings confirm the expected level of energy consumption reduction presented previously by Buzelin et al. (2005).

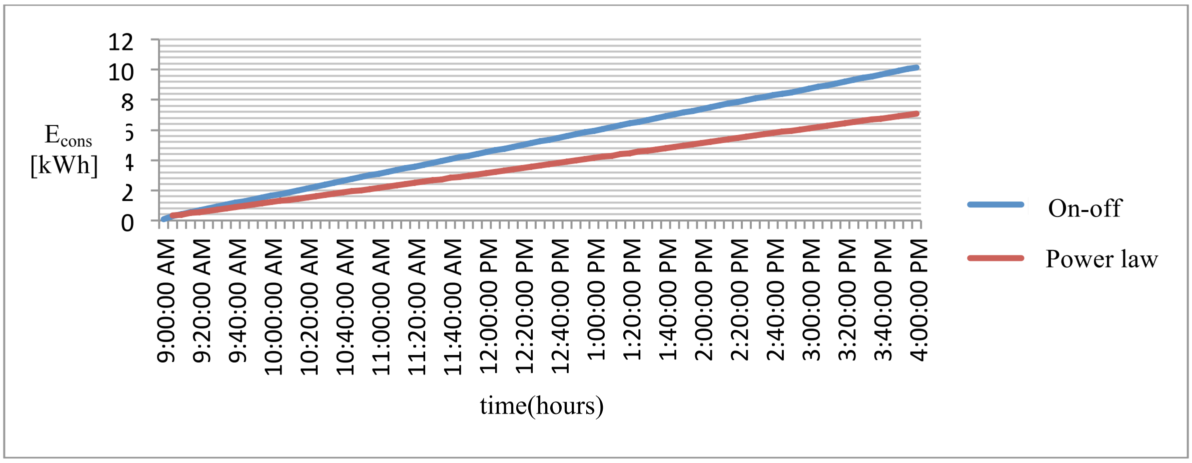

Figure 3. On-off and closed loop (Power law) refrigeration system energy consumption comparison.

5. CONCLUSIONS

An alternative solution to reduce energy consumption in existing domestic and industrial refrigeration systems is proposed and introduced. A typical refrigeration unit was modified in the laboratory, receiving a novel PLC (Programmable Logic Controller) and frequency inverter module (kit).

Comparison of temperature measurements in the thermal chamber of the proposed system and of a traditional "on-off" system demonstrated that the closed-loop power law controlled system shows a much smaller variation of cold chamber internal temperature allowing a fine tuning of the actual temperature around the established setpoint temperature. Moreover, an electrical energy consumption economy of approximately 34% was achieved in a seven-hour duration test in comparison with the traditional on-off system, under the same operating conditions.

This work has shown the potential of the proposed system to be implemented on any existing air conditioning and refrigeration plants. The necessary adaptations would be simple and require low financial investment.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Buzelin, L.O., 2003. Concepção e Desenvolvimento Teórico Experimental de um Sistema de Refrigeração Inteligente. Tese de Mestrado. Curitiba: Universidade Federal do Paraná.

Buzelin, L.O., Amico, S.C., Vargas, J.V.C., and Parise, J.A.R., 2005. Experimental development of an intelligent refrigeration system. International Journal Refrigeration, Vol. 28, pp. 165–175

Garcia, F.M., Bandarra Filho, E.P., 2006. Desempenho Energético de um Sistema de Refrigeração Aplicando o Controle Adaptativo Fuzzy, 16° Simpósio de Pós-Graduação em Engenharia Mecânica.

Li, B., Otten, R., Chandan, V., Mohs, W.F., Berge, J. and Alleyne, A.G., 2010. Optimal on–off control of refrigerated transport systems. Control Engineering Practice, Vol. 18, No. 12, pp. 1406-1417.

Maya, P.A, Leonardi, F., 2010. Controle Essencial, São Paulo: Editora Pearson.

Parreira, E.P. and Parise, J.A.R., 1993. Performance analysis of capacity control devices for heat pump reciprocating compressors. Heat Recovery Syst CHP, Vol. 13, No. 5, pp. 451-561.

Silveira, R.S. and Santos, W.E., 1999. Automação e Controle Discreto, São Paulo: Editora Érica.

Tassou, S.A. and Qureshi, T.Q., 1994. Performance of variable-speed inverter motor drive for refrigeration applications Comparative performance evaluation of positive displacement compressors in variable-speed refrigeration. Computing & Control Engineering Journal, Vol. 5, No. 4, pp. 193-199.

Tassou, S.A. and Qureshi, T.Q., 1997. Dynamic mode performance evaluation and energy analysis of mains and inverter driven refrigeration tion of positive displacement compressors in variable-speed refrigeration. J. of Power and Energy, Vol. 211, No. 4, pp. 339-346.

Tassou, S.A. and Qureshi, T.Q., 1998. Comparative performance evaluation of positive displacement compressors in variable-speed refrigeration. International Journal of Refrigeration, Vol. 21, No.1, pp. 29-41.

Vargas, J.V.C. and Parise, J.A.R., 1995, Simulation in transient regime of a heat-pump with closed-loop and on off control. International Journal of Refrigeration, Vol. 18, No. 4, pp. 235–243.

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