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Predictive Functional Control of Superheat in a Refrigeration System using a Neural Network Model

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Abstract: This paper compares three methods for control of the superheat in a refrigeration system. A traditional gain scheduled PI-based controller, a predictive functional controller (PFC) and a predictive functional controller with a neural network model (PFCNN). The aim is to investigate the performance of the three controllers with respect to disturbance rejection measured both at the superheat deviation from the reference and the actuation of the expansion valve. The controllers are designed and tested on a laboratory set-up. The performance of the controllers turns out to be similar and distinguish between the concepts must be based on other parameters like tuning and demands for computational power.

Keywords: Refrigeration system control, Predictive control, Neural networks, PID control.

1. INTRODUCTION

Refrigeration systems are widely used and among the most electrical energy consuming equipment in supermarkets. Refrigeration systems normally contain a refrigerant operating continuously between vaporization and compression. This process is implemented by a valve, an evaporator, a compressor and a condenser, and this set-up remains to a considerable extent the same in most refrigeration systems. The details of the vapour compression type refrigeration process are not given here, but can be found in e.g. Vinther (2013).

Larger refrigeration systems are normally controlled by three SISO PI-controllers. One is controlling the compressor to achieve an appropriate pressure in the evaporator ensuring a suitable saturation temperature. The condenser fan velocity is similarly PI controlled to ensure a certain condensation temperature. Finally the superheat is controlled using the opening degree (OD) of the expansion valve. The control of the superheat is in focus in this work. Different control concepts has been investigated in Vinther (2013), Rasmussen et al. (2009), Elliott et al. (2010), Vinther et al. (2013) and Vinther et al. (2012).

Super-heating of the refrigerant beyond the evaporation temperature is important, since no superheat means that two-phase refrigerant will enter the compressor and increase the power consumption and wear. This means that the flow through the valve must be kept at a level, where all the refrigerant is evaporated before it reaches the compressor. At the same time, it is important to have as much two-phase refrigerant in the evaporator as possible, to increase the heat transfer and thus optimize the refrigeration process. So a key variable, which greatly affects the efficiency of a refrigeration system, is the superheat, which again is an indirect measure of the filling of the evaporator. Normally the superheat is measured using the saturation pressure in the evaporator and the outlet vapour temperature at the evaporator output; these are combined to give the superheat. In our work we will compare three different controllers namely a gain scheduled PI controller, a predictive functional controller (PFC) and a neural network based PFC. PFC has been investigated for superheat control in Changenet et al. (2008) and Fallahsohi et al. (2009), with promising results. PFC with a neural network model has been suggested for highly non-linear systems, Yang et al. (2005) and Guo (2006); the present system is non-linear especially in the small signal gain, which could justify adding a neural network model to PFC. The control concepts are tested on a full scale laboratory set-up.

Most refrigeration systems are equipped with computers not suited for large computational tasks. The gain scheduled PI controller and the PFC with fixed difference equation model demands few computations. A trained neural network will not increase the computational effort considerably, but the training of a neural network constitutes a computational problem and must be done prior to commissioning.

Section 2 describes the laboratory set-up. The modelling of the expansion valve and the evaporator is presented in Section 3. Section 4 explains the control strategies and controller adjustments, Section 5 provides a comparison of the three control concepts and concluding remarks are finally given in Section 6.

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2. DESCRIPTION OF THE TEST SET-UP

A refrigeration system with full scale components is available at Aalborg University. A simplified schematic of the test set-up is presented in Fig. 1. This system has an approximate maximum cooling capacity of 4 kW and water is circulated on the secondary side of the evaporator in a circuit with a 60 litre water tank, a pump, and a heater. The refrigerant is R134a and the system also consists of a scroll compressor, a condenser unit, and interchangeable expansion valves; this can be either a stepper motor, EEV, or a thermostatic expansion valve, TEV. It is possible to control the OD of the EEV valve. The power to the water heater is controllable and can be seen as a disturbance to the system. The condenser pressure is controlled using the frequency of the condenser fan ensuring a reference pressure. The suction pressure P_e is controlled using the scroll compressor frequency. Sensors measuring temperatures and pressures, with a sampling interval of 1 second, are indicated in the figure. A more detailed description of the set-up can be found in Vinther (2013).

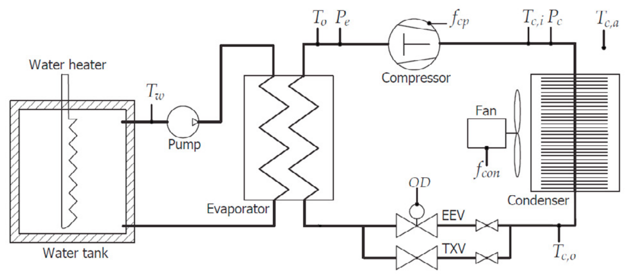

Fig. 1. Refrigeration laboratory system test set-up (a water chiller system), Vinther (2013).

3. MODELLING OF SUPERHEAT

The evaporator superheat control set-up in focus is illustrated in Fig. 2. Pressure P_e and the outlet temperature T_o from the evaporator are measured. The pressure P_e is converted to the corresponding saturation temperature T_e; this is subtracted from T_o giving the superheat temperature T_{sh}.

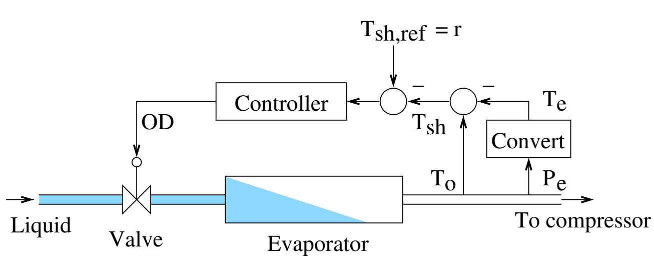

Fig. 2. Control of the superheat using the valve OD.

A small signal model from the valve OD to the superheat can be described by a first order system with delay, Vinther (2013), Rasmussen et al. (2009), Vinther et al. (2013)

$$\hat{T}_{sh}(s) = \frac{K}{\tau s + 1} e^{-T_d s} \hat{OD}(s), \qquad (1)$$

where ˆ indicates small signal values, K is the small signal gain, τ is a time constant and finally T_d is a time delay.

The small signal gain can be found from an experiment, see Fig. 3. In the experiment OD is slowly increased from 40.5% to 43.2%. The absolute value of the superheat is measured and is going from 15^oC to 2^oC; the small signal gain is the slope of this curve and can be found by making an approximation to the absolute superheat followed by finding the derivative of the approximation.

A potential approximation of the curve T_{sh} as function of OD is Vinther (2013)

$$T_{sh} \approx -k_1 arctan(k_2(OD - \bar{OD})) + \bar{T}_{sh}, \quad k_1, k_2 > 0, \; (2)$$

where bar's are offsets and k_1, k_2 are parameters. The four parameters are fitted to the graph and plotted in Fig. 3. The small signal gain is now found as

$$K = \frac{dT_{sh}}{dOD} = -\frac{k_1 k_2}{1 + (k_2(OD - \bar{OD}))^2}, \qquad (3)$$

which is also shown in Fig. 3 along with a simple numerical derivation.

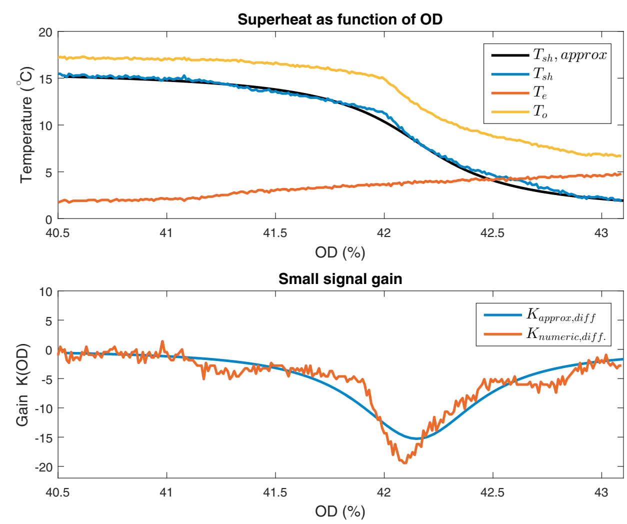

Fig. 3. Measured superheat as function of OD (upper plot). Small signal gain (lower plot).

It is seen in Fig. 3 that the gain K is very dependent of the OD value. For varying outdoor temperatures, $T_{air,o}$, or water heater powers, the cooling capacity is changed, meaning that the OD has a different operating point given as the center point in the *atan* function. Measurements indicate that shape of the *atan* function is the same for all center points giving the same small signal gain profile.

To overcome the variations caused by changing cooling capacity it is appropriate to have integral action in the controller. The variations in small signal gain can either be solved by gain scheduling or alternatively by use of a neural network.

4. CONTROL CONCEPTS

The aim of the superheat control is to maintain a constant (and low) superheat. In larger refrigeration systems the superheat is controlled using a standard PI controller, this will be the underlying basis for benchmarking the controllers. The two other controllers have their point of origin in predictive functional control (PFC) where the first is based on Richalet et al. (2014) and Richalet et al.