

# Reinforcement Learning Control of Transcritical Carbon Dioxide Supermarket Refrigeration Systems

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## Abstract:

Commercial refrigeration systems consume a substantial amount of electrical energy, resulting in high indirect global warming impact due to greenhouse gases emissions. The multitude of different system configurations, system complexity, component wear, and changing operating conditions make efficient operation of this kind of refrigeration systems a difficult task. This paper presents an investigation of machine learning for supervisory control of a supermarket refrigeration system. In particular, a reinforcement learning algorithm for a CO<sub>2</sub> booster refrigeration system is designed by exploiting the Matlab-based “SRSim” simulation tool. The reinforcement learning controller learns to operate the refrigeration system based on the interaction with the environment. The analysis shows that learning control is a feasible model-free technique to find a suitable control strategy for demand-side management in a smart grid scenario.

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*Keywords:* Commercial Refrigeration Systems; CO<sub>2</sub>; Control; Reinforcement Learning.

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## 1. INTRODUCTION

Commercial refrigeration covers a wide range of applications and it is the part of the cold chain which comprises equipment mainly used in retail outlets for preparing, holding, and displaying frozen and fresh food and beverages (Mota-Babiloni et al., 2015). In particular, supermarket refrigeration systems are one of the most energy-intensive systems and they produce a significant global warming impact due to greenhouse gases emissions (Rivers, 2005; James and James, 2010). The design, the commissioning, and maintenance phases as well as the store volume play an important role to reduce the energy consumption in supermarket refrigeration (Mossad, 2011; Evans and et al., 2014; Bahman et al., 2012). Beside this, monitoring and control systems, in addition to the essential temperature control of food products, can also offer energy saving potential. Due to the simple control policies most commonly used today in supermarket refrigeration, a non-negligible unexploited potential for energy and cost reductions exists. For example, refrigeration systems have been proven to be highly potential consumers for Demand Response (DR) implementations (Goli et al., 2011). Demand response provides an opportunity for consumers to play a significant role in the operation of the electric grid by reducing or shifting their electricity usage during peak periods in response to time-based rates or other forms of financial incentives. Examples of strategies for DR are: Real time pricing, in which the load level of consumers are optimized in response to electricity prices, and direct load control that manages the consumers energy consumption.

The implementation of such strategies are usually done by means of a hierarchical control structure where a goal (e.g. the electric power consumption) is specified to a consumer, then a high level layer (i.e. the supervisor) guarantees the goal by specifying set-points for local controllers, and a low level layer (i.e. local controllers) ensures the set-points are maintained. The supervisor, is the focus of this work.

Various control schemes have been applied in refrigeration systems, ranging from PID (Salazar and Mendez, 2014) to MPC (Model Predictive Control) (Shafiei et al., 2013a, 2014). It is worth noticing that, the multitude of different system configurations, system complexity, component wear, and changing operating conditions make optimal operation of refrigeration systems a difficult and time consuming task. System complexity also challenges the traditional model-based control design approach that turns out to be often tailored to specific system structures. In this paper the emphasis is instead on the development of a data-driven control strategy with a higher plug and play potential. Specifically, we use a Reinforcement Learning (RL) approach that directly learns the control policy by estimating a state-action value function through interactions with the environment. It is worth pointing out that, learning from experience is a fundamental characteristic of intelligence and it holds great potential also for artificial systems: for example, RL has been successfully applied in the field of HVAC (Heating, Ventilation, and Air Conditioning) applications (Liu and Henze, 2006).

In this paper, we consider a transcritical carbon dioxide refrigeration application. The use of CO<sub>2</sub> as a refrigerant can be very beneficial because of its good thermody-

dynamic properties and low environmental impact (Weber and Horning, 2015). This suggests that CO<sub>2</sub> supermarket refrigeration systems are a viable alternative to HFC-refrigerant-based systems, especially in cooler climates. Specifically, we have simulated a carbon dioxide booster refrigeration system by means of the “SRSim” tool (Shafiei et al., 2013b), which is a Matlab-based simulation environment useful for designing and testing control algorithms for supermarket refrigeration. In particular, we suppose that the CO<sub>2</sub> refrigeration system is controlled by means of a hierarchical structure and we focus on the design of the supervisor which has to provide the set-points for the local controllers in order to guarantee that the electric power consumption follows the reference set by a direct load control strategy. The results of simulations show that the model-free RL approach can be successfully applied for the supervision of a commercial refrigeration system.

The paper is organized as follows: Section 2 outlines a typical CO<sub>2</sub> booster refrigeration system; in Section 3 the RL method is described, while Section 4 depicts simulation examples related to the supervisory control of the system. Some concluding remarks are given in Section 5.

## 2. SYSTEM CONFIGURATION

### 2.1 CO<sub>2</sub> Booster Refrigeration System

We consider the basic layout of a typical CO<sub>2</sub> booster refrigeration system which includes several cooling units with two racks of compressors in a booster configuration, Fig. 1. The system operates as follows: the two-phase refrigerant at the receiver (REC, point 8) is split out into saturated liquid (point 1) and saturated gas (point 1b). The former flows into expansion valves where the refrigerant pressure drops to medium (point 2) and low (point 2') pressures, while the latter is bypassed by a bypass valve (BPV). The expansion valves (EV\_MT and EV\_LT) regulate both the medium (MT) and low (LT) air temperatures in the cooling units by manipulating the evaporators refrigerant mass flow rate. In the evaporators (EVAP\_MT and EVAP\_LT) the heat is transferred from the foodstuff to the refrigerant. The refrigerant leaves the EVAP\_LT and enters the low stage compressor rack (COMP\_LO) where it is compressed into a hot vapour at higher pressure. Then, all the refrigerant mass flows from COMP\_LO, EVAP\_MT and BPV outlets are collected by a suction manifold (point 5) where the pressure is increased again by the high stage compressors (COMP\_HI). Upon leaving the COMP\_HI, the vapour enters in the condenser where heat is transferred from the refrigerant to the surrounding. At the outlet of the high pressure control valve (CV\_HP), the pressure drops to an intermediate level and the refrigerant, which is now in two-phase, flows into the receiver and the cycle is completed. Further details on the thermodynamic analysis of such kind of systems can be found in Ge and Tassou (2011).

### 2.2 Hierarchical Control

We consider the scenario in which the smart grid uses a direct control approach for the demand-side management. In particular, the commercial refrigeration system has to follow the power reference (the goal) set by the grid in

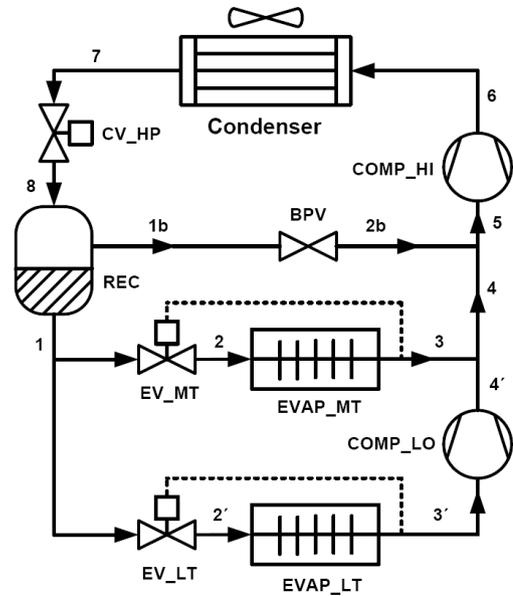


Fig. 1. A typical CO<sub>2</sub> booster refrigeration system which includes several cooling units with two racks of compressors (Shafiei et al., 2013b).

accordance with its storage and consumption limitations. More specifically, we suppose that the refrigeration system is managed by means of a hierarchical control scheme with two layers Fig. 2:

- (1) the supervisor (high layer), which specifies the set-points (e.g. compressors suction pressure and display cabinets air temperature);
- (2) the local controllers (low layer), which maintain the set-points specified by the supervisor.

The supervisor is the focus of this work; the aim is to determine the sequence of set-points for the local controllers over a finite time horizon to guarantee the goal set by the grid, while satisfying operating constraints. It is worth noticing that, the supervisor can be a simple standard regulator which regulates the power consumption or a more advanced algorithm such as MPC. These kind of algorithms is often designed and tuned by exploiting experts' knowledge or/and prediction models.

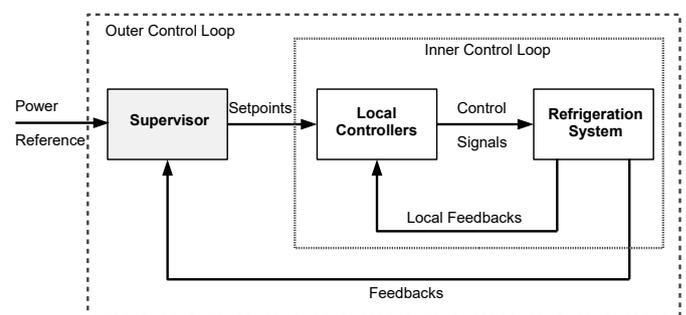


Fig. 2. The hierarchical control scheme.

## 3. MODEL-FREE CONTROL

Model-based approaches can be usefully employed to design cost-effective controllers. On the other hand, obtaining a suitable model is a difficult task and the uncer-

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