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Grey-box modelling of a household refrigeration unit using time series data in application to demand side management

Fabrizio Sossan*, Venkatachalam Lakshmanan, Giuseppe Tommaso Costanzo, Mattia Marinelli, Philip J. Douglass, Henrik Bindner

DTU Elektro, Frederiksborgvej 399, 4000, Roskilde, Denmark

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ABSTRACT

This paper describes the application of stochastic grey-box modelling to identify electrical power consumption-to-temperature models of a domestic freezer using experimental measurements. The models are formulated using stochastic differential equations (SDEs), estimated by maximum likelihood estimation (MLE), validated through the model residuals analysis and cross-validated to detect model over-fitting. A nonlinear model based on the reversed Carnot cycle is also presented and included in the modelling performance analysis. As an application of the models, we apply model predictive control (MPC) to shift the electricity consumption of a freezer in demand response experiments, thereby addressing the model selection problem also from the application point of view and showing in an experimental context the ability of MPC to exploit the freezer as a demand side resource (DSR).

1. Introduction

Household refrigerators account for a noticeable share of the total residential electricity demand (e.g. 7% in the US [1]) and are gaining attention in the context of demand side management (DSM) [2–4]. Validated mathematical models and procedures for on-line system identification of refrigeration units are of importance for assessing their energy efficiency, predicting their power consumption and in application to intelligent energy management strategies to support power system operation, such as model predictive control (MPC) [5,6]. In the first part of this paper, we describe the application of a state-of-the-art grey-box modelling methodology to identify power consumption-to-temperature prediction models using experimental measurements from a conventional domestic freezer. The modelling effort aims to identify the model structure and parameters of the physical processes associated with the operation of the freezer, i.e. heat transfer and refrigeration cycle coefficient of performance (COP). Consumer behaviour modelling is not considered at this stage. In the second part of the paper, the proposed models are used to implement a MPC strategy in order to experimentally achieve a shift in the energy consumption of the freezer. The contribution of this paper is twofold. First, novel validated grey-box models for a domestic freezer are proposed. Existing models in the literature were mainly developed using first principle approaches (see for example [7–9]). So-called white-box models in application to demand side management do not allow to achieve any degree of differentiation when dealing with different units. This property does not make them suitable for future smart grid scenarios, where demand response built up from the contribution of heterogeneous populations of demand side resources (DSRs) is expected to play a central role in assuring reliable power system operation. On the contrary, grey-box models are adaptive by nature since they are estimated from measurements and potentially allow for tracking system changes on-line by reiterating the estimation procedure. A set of linear grey-box models for a domestic fridge was proposed in [10]. In this case, we extend the already existing literature by considering a domestic freezer and, especially, by including in the modelling performance assessment a nonlinear grey-box model based on the reversed Carnot cycle. Second, by implementing the consumption shift experiments in a real operating environment, we address the model selection problem from the specific perspective of the application, that is finally among the most relevant problems for DSM. Overall, we therefore provide a global assessment of grey-box modelling for refrigeration units analysing both the pure modelling performance and application. The structure of the paper is as follows. Section 2 describes the experimental setup adopted for the model identification and consumption shift experiments. Section 3 describes the grey-box modelling framework adopted

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* Corresponding author.
E-mail address: fabrizio.sossan@epfl.ch (F. Sossan).

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to identify the freezer models, which are therefore presented in Section 4. In Section 6, we perform an empirical evaluation of the thermal properties of the considered freezer with the objective of supporting grey-box modelling results. In Section 4, the models prediction performance are further assessed using validation data sets. Finally, in Section 7 a number of the proposed model are used in an MPC experiments with the objective of shifting the consumption of a freezer in the context of intelligent energy strategies for demand response applications.

2. Experimental setup

The experimental setup consists of a freezer equipped with temperature sensors, a power consumption measurements board and an external relay. The objective of the experiment is to collect the measurements for identifying the freezer models and to perform the energy shift experiments. The instrumented freezer (shown in Fig. 1) is a Bosch GSN40A21,[1] a commercially available domestic unit with 333 L capacity and a single-phase compressor. During experiments, the freezer was empty and with closed door. Temperatures are measured using 10k NTC thermistors, which can measure temperatures in the range −30 to 80 °C with an accuracy of ±0.2 °C at 25 °C and have a fast measurements response. Thermistors are connected to a 12 bit ADC through a resistance-to-voltage transducer. A total of 3 thermistors are used, 2 for measuring the freezer interior temperature at different heights and one for the room temperature. The freezer power consumption is measured using a DEIF MIC-2. This accuracy class 0.5 instrument is able to measure voltages and currents up to 400 V/5 A of magnitude on a three phases bus, although only one phase is used for this application. The controllable power plug determines the state (on–off) of the freezer. In order to override the internal action of the freezer thermostat, the thermostatic set-point is set to the lowest value, and the temperature of the freezer is allowed to vary only above this threshold. In this way, the activation of the freezer compressor depends only on the state of the external relay. All the sensors and instruments are connected to a PC and are accessed by a JAVA software application. Measurements and actuations are sampled at 1 s.

3. The grey-box modelling methodology

Grey-box modelling is a framework to identify and validate a mathematical model of a system incorporating its physical knowledge together with measurements from a real device. It consists of a number of steps, which are explained in the following.

3.1. Experimental design

A control signal commonly used for model identification is the PRBS (pseudo binary random signal), an on–off signal with fixed period and uniformly distributed random duty cycle that is able to excite the system to model in a wide range of frequencies. For identifying the freezer thermal models, a PRBS was used to set the state of the controllable power plug. To avoid damaging the freezer compressor, the PRBS cycles with on-to-off transitions shorter than 30 s were disregarded. By doing this, it was not possible to observe very short transients, which however are of limited interest since we target to capture the dominant system dynamics. Fig. 2 shows the set of measurements used for the model identification. In the upper panel plot, it is evident the effect of the PRBS on the freezer power consumption, that is characterized by activation cycles of random length. The time series are of appropriate duration for the purpose of thermal models identification as they are considerably longer than the slowest time constant of the system (≈4 h[2]). Two additional sets of measurements were collected to assess the models prediction performance (Section 6).

Fig. 1. The 333 liter domestic freezer used for the model identification and model predictive control (MPC) experiments.

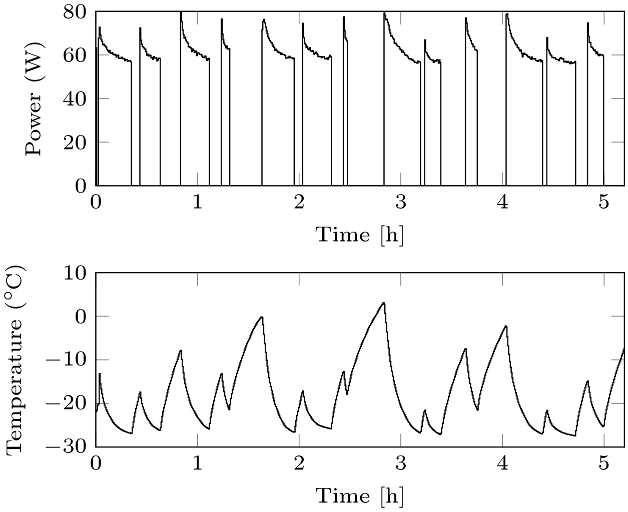

Fig. 2. The measurements used to identify the freezer thermal models: the freezer power consumption under PRBS regime after the post processing as described in Section 3.2 (upper panel) and temperature (lower panel).

3.2. Measurements post-processing

The measured physical quantities are the freezer and room temperatures and freezer total power consumption. Two freezer

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[1] The freezer belongs to Power Flexhouse, an experimental facility of DTU Elektro for testing demand side management strategies for smart grid applications.

[2] Approximatively estimated prior the model identification as 1/5 of the zero-input temperature transient duration.