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Comparison of control approaches for variable speed air source heat pumps considering time variable electricity prices and PV

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HIGHLIGHTS

- Study of complexity vs. performance of controllers for a variable speed heat pump.
- Rule based, predictive and model predictive controls (MPC) tested.
- Results show importance to consider different KPIs for controller testing.
- MPC outperforms other control approaches, even with forecast error.
- Larger storage only beneficial with MPC.

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ABSTRACT

The influence of different control strategies and boundary conditions on heat pump system performance are investigated in this study and the trade-off between complexity and performance of different controllers is addressed. For this purpose five different control approaches for a variable speed air source heat pump in a multi family house are compared for three different use-cases. The used controls differ in complexity and the use of external input data like price and weather forecasts. The use-cases are: Constant electricity prices, time variable electricity prices and PV self-consumption. Four different rule-based controllers are compared to a convex MPC approach, presented in this work.

Results show that the MPC approach reduces annual operating cost by 6–11% for constant electricity prices and 6–16% in the case of variable electricity prices. Rule-based approaches lead to cost reductions of 2–4%. MPC could increases PV self-consumption from 56% to 58% up to 64–71%. The rule base approaches are found computationally less demanding and easier to design. However fine-tuning has been considerable work and with changing boundary conditions rules had to be readjusted. It showed that increasing thermal storage without MPC is not beneficial and optimised controls are a prerequisite to benefit from increased storage sizes.

1. Changing boundary conditions and new opportunities for heat pump controls

Three developments will change the way heat pumps (HP) will be operated. First, the integration of heat pumps into smart grids [1]. In this context managing the demand side will be increasingly important to balance an increased electricity generation from fluctuating renewable sources. It has been shown that heat pumps, connected to thermal storage or actively using the building's thermal mass, can provide flexibility in operation, which can be used for tasks in the power system. In this context time variable electricity prices can be used as a way to align heat pump operation with the needs of the power system, which influences the boundary conditions for HP operation.

The second development is an increase of on-site photovoltaic (PV) electricity generation and the motivation to self-consume an optimal share of the generated electricity. This will influence the choice of control strategy and the boundary conditions for HP operation.

The third development is the availability of forecasts and cheap computation capacity on a controller level, which led to an extension of existing control approaches by:

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1. The use of forecasts for loads, PV electricity and prices to derive a control trajectory.
2. The use of heuristics or optimisation methods to derive a control trajectory.

Those approaches now compete with existing rule-based non-predictive approaches.

A central question is to which extend additional information and additional complexity improves controller performance, and to what extend new control approaches are needed to successfully integrate heat pumps into a smarter and increasingly renewable electric system? Furthermore the question is how the different control strategies and smart grid boundary conditions will impact heat pump system operation?

1.1. Previous work

Advanced controls for heat pump systems have been studied in the past mostly with a focus on model predictive controls (MPC). First studies on MPC with heat pumps for space heating under time variable electricity tariffs have already been presented in 1988 [2]. The maximum principle of optimal control is applied to derive control trajectories which are reported to be optimal. The solution has bang-bang characteristics and the control task is reduced towards finding an optimal switching point for the heat pump. [3] uses a linear optimal control formulation for MPC to control heat pumps used for heating residential buildings with a floor heating system. Thermal capacity of the building is used to shift electricity consumption to periods with low electricity prices. For the given case, cost savings of 25–35% are reported. In [4] linear MPC is used to control a multi energy system comprising of a heat pump, slab cooling, an electric water heater, lead-acid battery storage, and photovoltaic panels. The building energy system is operated with respect to day-ahead and real-time prices. [5] presents MPC of domestic heat pump directly connected to a Danish single-family house. Using a constant COP, a linearised building model and a convex cost function, the optimal control problem is solved using a convex solver. For the given case the resulting savings on an example winter day are within the range of 7–12% compared to a conventional control approach. [6] presented a set of model predictive control approaches using a time dependent COP formulation and a linearised building model. This was done for the case of On-Off heat pumps with pulse width modulation used for space heating in single family houses. The objective was tracking a building reference temperature while minimising electricity costs, which was achieved by solving a quadratic optimisation problem. A cost reduction of up to 13% was reported. [7] extended the approach towards adaptive controls, highlighting the importance of parameter identification schemes and predictions. [8–10] extends the MPC approach accounting for uncertainties in weather predictions further. Stochastic MPC is used to satisfy temperature constraints of different buildings at minimum costs. For the presented cases it was shown that the stochastic approach outperforms a conventional MPC approach. Iterative linearisation is used to estimate a system model used for solving a convex optimal control problem at each receding horizon step.

In [11] a comparison of convex and non-convex problem formulation is presented for an On-Off heat pump, showing that the non-convex formulation results in 4–6% less costs. This is extended in [12] towards a variable speed heat pump. The focus of both papers is on using building thermal mass and floor heating's thermal inertia as storage. ACADO direct multiple shooting is used to solve the optimal control problem.

[13] compares a rule-based and a model predictive controller for an energy management system including batteries, a ground source heat pump, PV, shiftable appliances and thermal storage. Dynamic programming is used to solve the resulting non-linear control problem. Here the non-linearities in the heat pump are respected. Stratification of the thermal storage is neglected. Different scenarios for batteries and thermal storages size are investigated. It is shown that the dynamic programming approach significantly outperforms the rule-based approaches with respect to annual operation costs, however with respect to self-consumption the benefit of the dynamic programming approach are not as dominant.

1.2. Contribution of this work

The previous studies highlight the potential of improved controls with a focus on MPC. The considered performance criteria are mostly annual operating cost or PV self-consumption rates. Whereas a detailed analyses of the operation of the heat pump, the storage and the back-up heater with respect to a more comprehensive set of key performance indicators (KPI) is missing. Frequently this is not possible as the used models in the presented studies do not cover non-linearities of the heat pump, stratification of the thermal storage (also criticised in [14]) or are directly based on the results of the optimal control problem.

By the use of appropriate models, controllers and a broad range of key performance indicators this work provides a comprehensive picture about the different controls options and important control design parameters. Each controller is tested for different boundary conditions and storage sizes.

In most studies MPC approaches are compared to one single and often poorly designed controller for benchmark. This might lead to an overestimation of MPC. This is why a considerable amount of research time was spent to fine-tune the benchmark controllers. Four different rule-base controllers, including a predictive controller are compared to MPC to provide a differentiated picture of the trade-off between complexity and performance. Furthermore the MPC is assessed in the presence of forecast errors, with an interesting result (see Section 4).

Some of the MPC approaches presented in literature are based on non-linear programming methods, which can be computationally intensive and might hinder deployment in the field. The presented MPC approach based on quadratic programming and is lean enough to be implemented on real devices, as done in the GreenHP project [15].

The depth of analyses and the discussion of results as shown in this paper are more detailed than in any of the previous work, thereby providing a more comprehensive picture of important operational aspects and the trade-offs between the different controllers and control goals, which are discussed in Section 5.

2. Models used

The different controllers are tested for a multi family house with six living units, each with two residents, located in Potsdam, Germany. The house is equipped with a variable speed air source heat pump connected to a stratified thermal energy storage tank for domestic hot water (DHW) and space heating (SH). DHW is prepared using an external heat exchanger (fresh water station FWS). A 10 kWp PV plant is mounted on the roof, southward oriented and 35° inclined. The modelled system is shown in Fig. 1 and explained in the following.

2.1. Electricity and DHW demand profiles using synPRO

Electricity demand for appliances is modelled using the stochastic bottom-up model synPRO. The approach is introduced and validated in [16]. It is based on the Harmonized European