Model Predictive Control for Electric Heat Pumps based on a Multi-Objective Optimization

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***Abstract*—This paper introduces an innovative control concept for electric heat pumps (EHP) applying a multi-objective optimization. By using market, grid, electricity price and storage signals, an optimum solution fulfilling different objectives to a certain extent is reached. The results show that the fulfillment of all objectives depends mainly on the system sizing and on the signal composition. Simulations show, that a solution fulfilling the objective function in compliance with all restraints can be reached. With the developed control scheme a significant shift of the EHP operation from high price periods towards low price periods can be achieved. Further, grid specific violations and market imbalance have been tackled through a concept bringing different objectives together.**

Keywords- electric heat pump; model predictive control (MPC); multi-objective optimization

I. INTRODUCTION

Due to the rising share of decentralized energy resources (DER) and the electrification of the heating and transport sectors, the German low voltage (LV) grids will be facing more operational issues in the future as these trends are still ongoing. However, the integration of renewables is not only a local grid issue but also a challenge at the system-wide level. The sometimes negative electricity stock prices make this noticeable.

Energy management concepts, which enable an increase in system flexibility are able to solve balancing and grid problems. These measures are preferred to grid reinforcement and extension as they typically have lower investment costs.

In order to support the integration of renewables in LV grids, different electric heat pump (EHP) control concepts have been proposed in the past. However, all these concepts are either limited by the storage systems' characteristics to which the heating systems are connected or by the control concept as such. In previous works the flexibility gain through innovative storage concepts has been assessed [1]. This paper proposes a control strategy where various stakeholders can benefit from.

II. STATE OF THE ART OF HEAT PUMP CONTROL

A. Conventional control

Conventional EHPs are controlled based on a heating curve, which mainly depends on the building and on the heating system. This characteristic curve defines for each ambient temperature a set point outlet temperature of the EHP in order to keep the building at a required room temperature. Thus, the EHP is controlled in a way that this outlet temperature is guaranteed. This is achieved by means of a two-point controller, which switches the EHP within a hysteresis in order to respect the minimum on- and off-durations and to prevent the compressor from fatigue.

In this case, the EHP operation is directly coupled to the heat demand of the building, as the only control value is the outlet temperature.

B. Advanced control

Recent research investigations show various other control schemes, which have been used in order to improve the EHP operation and provide additional flexibility for the system. These control schemes can be divided into three classes depending on the considered system and thus the extent of the actions:

- "Central" as proposed in [2]. The EHP operation follows the global electricity stock price. During low price periods the EHP is more likely to be in operation than during high price periods. With this control scheme imbalances in the central European System (CES) are counteracted, as extreme load situations (peak loads and very low loads) are avoided. Thus, the integration of renewables, which contribute to low electricity market prices, is supported by a market driven concept.
- "Local" as introduced in [3]. The EHP control addresses a local problem like overload problems in a LV grid.
- "Decentral" as described in [4]. This control method tackles for example self–consumption optimization and minimizes the costs of electricity for the end customer.

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III. System Design

In order to examine the developed control concept, a system model based on a residential building equipped with a heat pump and a buffer storage has been designed. This reference building has a yearly heat demand of 150 kWh/m² and corresponds to the German energy efficiency class E of the EnEV standard [5]. The dynamic building model has been the subject of former work [1].

The sizing of the EHP is determined based on the heating load of the building in the considered climate region 12 of the DWD [6] and has a nominal thermal power of 12.1 kW and a power factor of 0.72. A detailed description of the model can be taken from former publications [7, 8].

The size of the water storage tank has been determined based on a recommendation of EHP manufacturers [9]. The volume of the considered tank is 800 l.

IV. Control Concept

A. *Control objective*

The main objective of each EHP control is to guarantee that the heat demand of the building is met during the whole heating period. In addition, the proposed control concept fulfills the following sub objectives:

- Reduce active power balancing issues.
- Provide flexibility to the LV grid in order to avoid grid specific limit violations.
- Minimize the operational costs for the end costumer.

These three sub objectives address all of the three above described levels of action: central, local and decentral.

B. *Status variables*

The status variables describe the forecasted situation of a system over time:

- m ("market") is a central variable and reflects the situation of a wholesale electricity market. m is based on the German day-ahead EPEX stock price.
- n ("network") is a local variable which describes the situation of a LV grid. This can be determined either by power flow calculations or by estimating the LV grid loadings and voltage levels. For both cases a load and generation forecast is necessary.
- l ("level") is a decentral variable and reflects the storage level of the water tank.
- p ("price") describes the end customer electricity price. The price structure can be any scheme from static to fully dynamic, depending on the availability of the tariffs offered by the energy supplier.

These four variables are inputs for the constraints and the objective function of the optimization problem of the MPC.

C. *Constraints*

For each discrete time step t each of the status variables m, n and l should respect certain limits. A violation of either the lower limit (ll) or the upper limit (ul) leads to an undesired state of the system. Depending on their specifications, the status variables can be assigned to three different levels as described in Tab I.

TABLE I. Specifications of the status variables

Level	**Status variables**		
	m	***n***	***l***
I	High electricity stock price level due to generation scarcity, bottlenecks or active power imbalance.	High residual load or/and a low voltage level.	The storage level exceeds the maximum storage capacity due to the limited outlet temperature of the EHP.
II	Average electricity spot price indicating that the balance is not at risk.	No risk for grid limit violation.	The storage level complies with the boundaries.
III	Low electricity stock price due to high renewable generation.	Low or negative residual load or/and a high voltage level.	The storage level is lower than the minimum value for serving the heat demand of the building.

Based on the three defined levels the forecasted status variables can be represented by a color code (cc) – in the style of a traffic light signal – illustrating the needed action to take in order to counteract an undesired state. The relationship is shown in Tab. II. Note, that green doesn't mean that the system has no limit violations but the colors reflect the suggested on/off signal of the EHP.

TABLE II. Overview of levels in term of limit violation, cc and preferred EHP operation

Level	**Probability of limit violations**	**cc**	**Preferred EHP operation**
I	high	🟥	off
II	low	🟨	–
III	high	🟩	on

D. *Objective function*

An optimal solution meeting the a.m. constraints can be selected based on minimizing the operational costs for the optimization horizon. These costs correspond to the sum of the products of the electrical energy consumption $E_{\mathrm{el},i}$ of the EHP and the corresponding electricity price p_i for each time step i of the optimization horizon. An optimization horizon of 24 hours has been chosen and corresponds to the prediction horizon of the MPC. The time step is set to 15 minutes.

E. *Control process*

For each time step the status variables m, n and l are forecasted, assigned to one of the levels and represented by the cc.

In order to determine the action to take for achieving the different objectives described in section A, a prioritization is needed. As providing the needed heat demand is the main objective, the constraint related to the storage level has the highest priority. The LV grid has the second highest priority. The lowest priority is given to the market as this has many other actors and mechanism to support its balance. Hence, the priority decreases with increasing system extent (decentral, then local and then central). This prioritization and the resulting EHP switching signal y_{cc} are illustrated in Fig. 1.

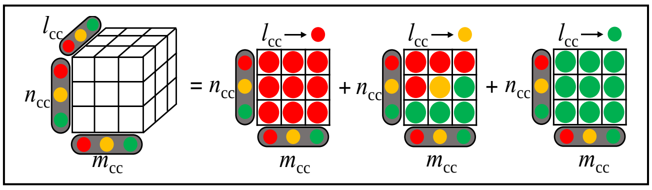

Figure 1. EHP switching signal y_{cc} based on the status of m, n and l

As each status variable m, n and l can have one of the three defined cc, a total number of nine options is possible.

If the storage level l is beyond the ul (cc=red) or below the ll (cc=green) the EHP will be either in the must stop (off) or in the must run (on) mode, independent of the values of the other status variables n and m. In case that the storage level l is in compliance with the boundaries (cc=yellow), the cc of the LV grid signal n decides about the switching of the heat pump without taking into account the market status described by m. Only if both storage level and LV grid status are in compliance with the boundaries (cc=yellow) the EHP switching will be based on the market status.

In case of no limit violations for all three status variables m, n and l, both operation modes – on and off – are admissible. This leads to two possible solutions (on or off) for the considered time step. The optimum for the control horizon (24 hours) is then obtained using the objective function. The solution is found by a full enumeration approach.

V. EVALUATION OF THE CONTROL CONCEPT

A. Control scheme

In order to demonstrate the control concept, grid and market signals reflecting a typical situation of an average day have been chosen. These signals are shown in Fig. 2. e) as cc for n_{cc} and m_{cc}. Each of the signals shows 96 different time slots corresponding to the length of the time steps (15 minutes).

The grid signal n_{cc} represents the residual load level of a typical LV grid with DER. In the morning and evening the load is high (n_{cc}=red) and during noon low (n_{cc}=green) due to the PV in feed. The market signal m_{cc} is connected to the wholesale electricity market and reflects more or less the residual load of the whole bidding zone. A similarity to the grid signal during the morning and the evening can therefore be observed. High residual loads lead to high electricity stock prices (m_{cc}=red). However low price periods, which correlate with low residual loads (m_{cc}=green) occur mostly during the first 5 hours of the day. Furthermore, the storage level status is illustrated via l_{cc} in Fig. 2. e).

These three signals lead according to the procedure described in Fig. 1 to the switching signal y_{cc} shown in Fig. 2. d). The switching signal shows the must run times (y_{cc}=green), the must-stop times (y_{cc}=red) and free-choice times (y_{cc}=yellow), during which the EHP can be either on or off depending on the operational costs.

The end customer price p has been chosen in accordance to the spot electricity price as shown in Fig. 2. c). The price level p_1, corresponds to low price periods, p_2 to the average ones and p_3 to the highest price periods. Furthermore, a spread of 10 % between the three price levels has been assumed. i.e. p_1 is 10 % lower than p_2 and p_3 is 10 % higher than p_2.

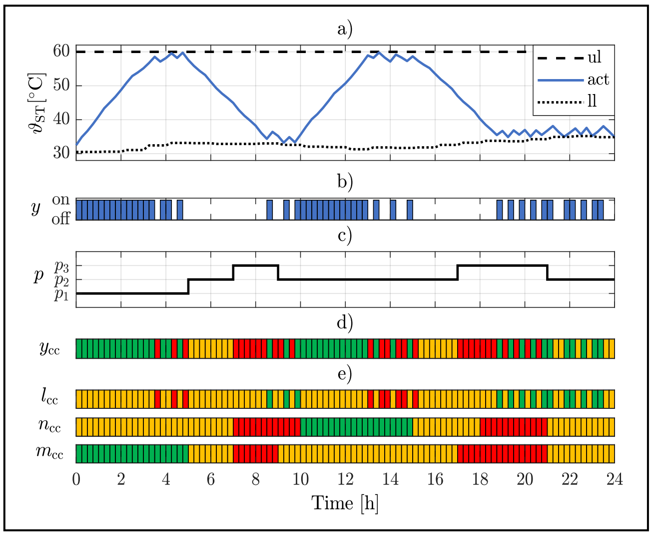

Figure 2. Exemplary control scheme showing a) the resulting storage level, when applying b) the optimal EHP switching signal resulting from the minimization of operational costs based on c) the electricity price and the d) the possible switching options following from e) the market, grid and storage constraints

Fig. 2. b) shows the resulting switching signal y, which fits best to the constraint fulfillment and leads to a minimum of operational costs. This switching signal leads to the actual (act) storage level ϑ_{ST} shown in Fig. 2. a) which respects the lower storage level (ll) and the upper storage level (ul) during the whole optimization horizon.

B. Constraints fullfillment

The fulfillment of the constraints depends on the priority given to each of the signals, on the storage capacity and on the ambient temperature distribution of the chosen day. Furthermore, the signal sequence over time is decisive for the fulfillment of the constraints. An alternating signal with many changes in the status and consequently in the cc is more likely to get fully fulfilled than a signal with long periods of preferred run or stop times, as the storage capacity is limited.

Fig. 3 shows the amount of constraint fulfillment. As the storage level signal has the highest priority, a 100 % fulfillment is reached and this should always be the case. A violation of this constraint is an indicator for an insufficient EHP power or a general system sizing problem. The market signal shows a higher constraint fulfillment than the LV grid signal although it has a lower priority. This is on the one hand due to the low storage level at the beginning of the time horizon, which is in favor for the market signal fulfillment and on the other hand due to the correlation of the market signal and the price signal, which leads to an optimal solution favoring the market signal fulfillment.

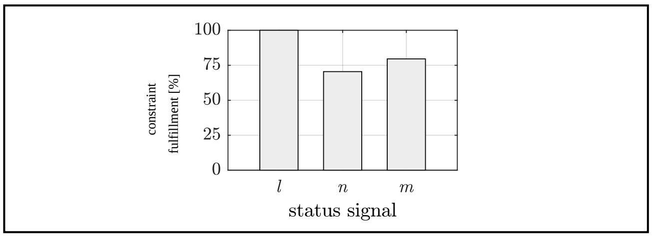

Figure 3. Constraint fulfillment of the status signals

C. Comparison to conventional control

Both conventional (conv) and the proposed optimized (opti) control schemes have been compared in terms of their operating modes. Fig. 4. b) and c) show the EHP switching signals for both cases. The resulting temperature profiles in the buffer storage are shown in Fig. 4.a). A clear difference in operation is observed. The conventional control is characterized through a cyclic on/off alternation due to the hysteresis control. The hysteresis has been set to 4 K, which is a typical setting for present conventional EHP controls. The optimized one is driven by the above described factors (constraints and objective function) and therefore uses the complete available storage capacity to buffer the energy, when needed.

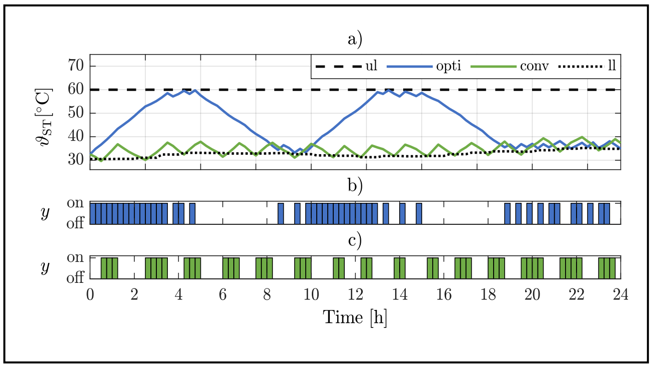

Figure 4. Comparison between the output of the developed control scheme and the conventional control

Both control schemes have been assigned the same price signal in order to examine the difference in term of shifting the operation times toward low price periods. Fig. 5) shows the frequency of occurrence of each price level for the two modes of control. A clear shift from high to low price periods is noticed. The frequency of exploiting low price levels increases from 23 % to 37 % whereas the frequency of exploiting the highest price level decreases from 25 % to 13 %.

As higher storage temperatures lead to a lower efficiency of the EHP and consequently to a higher electricity consumption, an increase of 24 % in comparison to the conv case is noticed. Through the better use of low price periods as shown in Fig. 5 the operational costs show a lower increase of 20 %. Consequently, with the given tariff scheme, the business case is still negative from an end-customer perspective as the chosen spread is not high enough to compensate the loss in efficiency. Alternatively, a compensation for the ability of providing flexibility could be offered.

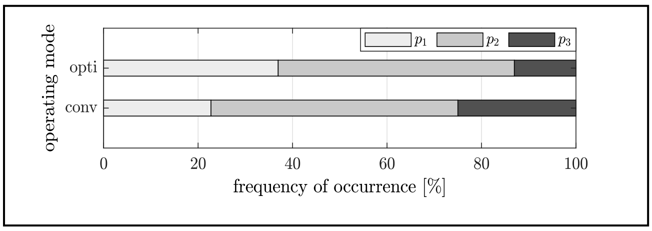

Figure 5. Comparison of the frequency of occurrence of the price levels of the conventional (conv) control with optimized (opti) control

VI. CONCLUSION AND OUTLOOK

The application of a multi-objective optimization taking into account the central market status, the local grid status, the decentral storage level status and the electricity price leads to a promising result. All objectives of the control were fulfilled to a certain extent within the available range of flexibility offered by the storage system. An oversizing of the storage or the application of a latent storage concept, as proposed in former works [1], would increase the signal response potential which is limited in the presented example. Furthermore, the introduction of a latent storage would solve the efficiency problem and make the concept attractive even for small price spreads.

Nevertheless, for the given system an optimal solution bringing together the main objective and all three constrains has been achieved.

As the system sizing is still the limiting factor for the fulfillment of the requirements, an assessment of the influence of higher storage capacities will be examined in future work.

REFERENCES

[1] A. Benzarti, M. Hamilius, S. Röhrenbeck, and W. H. Wellßow, “Potential of a PCM-Based Storage Concept combined with an Electric Heat Pump”, *3rd International Hybrid Power System Workshop, Tenerife, Spain, 08 - 09 May*, 2018.

[2] A. Benzarti *et al.*, “Smart Control of Heat Pumps and Thermal Storage Systems: An Approach to Support Future Distribution Grids”, *Conseil International des Grands Réseaux Électriques (Hg.) – Experiencing the Future Power System*, 2017.

[3] B. Friedel, “Smart Controls for Hybrid Heat Pumps May Solve Grid Congestion,” in *Heat Pumping Technologies Magazine*, pp. 25–28, 2016.

[4] A. Witzig, T. Straub, M. Hartmann, and T. Sonntag, “Fast Simulation Algorithm for PV Self-Consumption with Heat Pump Systems: Calibration Methodology with Comprehensive Dynamic Simulation Model as Reference,” *29th European PV Solar Energy Conference, Amsterdam*, 2014.

[5] Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden: (Energieeinsparverordnung - EnEV), 2007.

[6] M. Webs, T. Deutschländer, and J. Christoffer, “Testreferenzjahre von Deutschland für mittlere und extremeWitterungsverhältnisse TRY: Klimastatusbericht,” DWD, 2004.

[7] S. Röhrenbeck *et al.*, “Assisting Renewable Energy Integration by Price Based Load Shifting using Heat Pumps with Thermal Storage”, *Die Energiewende - Blueprint for the new energy age: ETG Congress Bonn, 28 - 29. November*, 2017.

[8] S. Röhrenbeck *et al.*, “Prädiktive Betriebsoptimierung drehzahl-variabler Wärmepumpen in Kombination mit preisvariablen Stromtarifen”, *Internet der Dinge: VDE-Kongress 2016 Mannheim, 7 - 8. November*, 2016.

[9] Viessmann Deutschland GmbH, Ed., “Planungshandbuch Wärmepumpen”; 2011.