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Market driven vs. grid supporting heat pump operation in low voltage distribution grids with high heat pump penetration – an Austrian case study

Roman Schwalbe[a]*, Martin Häusler[b], Matthias Stifter[a], Tara Esterl[a]

[a] AIT Austrian Institute of Technology, Donau-City-Straße 1, A-1220 Vienna
[b] Fachhochschule Technikum Wien, Höchstädtplatz 6, A-1200 Vienna

Abstract

The rising share of heat pumps in residential heating and cooling provokes increasing demands on future electrical power distribution networks. High penetration of heat pumps in low voltage grids might lead to network congestions and subsequent to the necessity of reinforcing a significant share of our existing grids in future. To use the existing infrastructure efficiently, some distribution system operators already offer special grid tariffs to customers that operate their heat pump grid friendly by avoiding operation during peak hours. On the other hand, in future customers may want to operate their heat pump marked driven to save energy costs. Especially a market driven operation of heat pumps might lead to high coincidence factors in energy consumption in low voltage grids with high heat pump penetrations.

This paper compares different heat pump operation strategies based on electrical power flow simulations coordinated with simulations of heat pump operation and the resulting impact on the customers comfort zones (room and hot water temperature). These operation strategies are applied in different penetration scenarios on three Austrian low voltage grids and simulated for typical days in winter with high heating demand. The resulting grid loading, voltages and the impact on the operational coincidence factor of heat pumps will be compared, and the pros and cons of the different operational strategies are discussed.

Keywords: heat pump; low voltage grid; distribution system operator; marked driven operation; grid supportive driven; penetratation

1. Introduction

1.1. Motivation

To reach the target setting given by the European Union for energy efficiency, energy services and share of renewable energy, the energy efficiency act (German: "Energieeffizienzgesetz") was decided in Austria in 2014 [1]. Electric heat pumps can be utilised for the implementation of the energy efficiency measurements in the domestic sector as well as for increasing the consumption of renewable energy since a transition from traditional energy sources for heating to electric energy is performed. Furthermore, thermal buffers in building mass and hot water enables electric heat pumps to provide energy services like offering flexibility on electricity markets.

Since electric heat pumps are a technically mature and economically feasible way for providing residential heating and cooling, the share of heat pumps continuously increased in the last years [2]. This observed rising share of heat pumps in residential heating and cooling provokes increasing demands on future electrical power

* Corresponding author. Tel.: +43-664-8157993; fax: +43-50550-6390.
E-mail address: roman.schwalbe@ait.ac.at.

distribution networks. High heat pump penetrations in low voltage grids might lead to network congestions and subsequent to the necessity of reinforcing a significant share of our existing grids in future [3].

1.2. The IEA HPP Annex42 Project

The IEA HPP Annex42 ("Heat pumps in smart energy grids for sustainable cities") project [4] elaborates and analyses the technical possibilities and economic/regulatory framework conditions for heat pumps used as flexibility resources. Furthermore the impact of demand shifting on the thermal loads is analysed. Also, the impact of a high density of households with electrical heat pumps on the low voltage (LV) grid is analysed within this project.

1.3. Grid congestions due to heat pump operation from the Austrian perspective

In the past information about electric heating, electric heat pumps or electric vehicles were rarely incorporated in power system planning of LV grids. This could lead to grid congestions in future depending on the future development of the regulatory framework. In Austria, households are nowadays typically fused with 25 A (=17 kW), with a typical contracted connection power of 4 kW. The coincidence factor of many households can decrease down to 0.2 and below depending on the number of households and its location in the grid [5]. Additional information like the usage of electric heating or the operation of heat pumps should be considered in the calculation, but currently not all distribution system operators (DSOs) do this in practise.

According to the Austrian grid code [6] no notification or permission of the DSO is necessary for the operation of motors up to 3.8kVA three-phase. Since domestic heat pumps have a typical consumption of 1-3 kW, households are allowed to operate the heat pump without any restriction from DSO side and without the need of the DSO's permission to operate them, nor the obligation to give any notification of the operation.

From this point of view, if the heat pump penetration increases in future, the synchronised and area-wide activation of heat pumps – e.g. due to market participation – can lead to grid congestions. To prevent such situations, some Austrian DSOs offer special heat pump tariffs that provide cheaper grid tariffs for the customers if the DSO is allowed to interrupt heat pump operation for a few hours in times of high grid load. Although this can be a cost-efficient alternative to grid reinforcement in many cases, customers are currently not legally obligated to use these tariffs depending on the technical connection conditions.

2. Methodology

This paper compares different heat pump operation strategies based on electrical power flow simulations coordinated with simulations of heat pump operation considering and maintaining the customers comfort zones room temperature and hot water temperature.

Simulations are performed for the case of (i) autonomous and independent heat pump operation, (ii) heat pumps controlled by the DSO to avoid grid congestion and (iii) heat pumps participating on markets. These operation strategies are applied on three rural Austrian LV grids that are simulated for time periods of one week in winter with realistic load profiles and weather/temperature conditions. The impact of the strategies on the grid voltages and the loading of the grid assets is evaluated and discussed.

2.1. Simulation framework

The power system simulation and analysis software Digsilent PowerFactory [7] is used for the simulation of the low voltage grids. The case study grids are modelled in the TN-C-S system [8] as it is common in Austria. A detailed four-wire modelling of the grid and an asymmetrical three-phase calculation is necessary since single phase loads can cause a significant voltage drop in the grid. In these grids, all heat pumps are modelled as three-phase symmetrical loads.

The heat pump models developed within the project iWPPflex [2] which are also used within the Annex42 project [4] have been realised in Dymola [9]. PowerFactory offers various interfaces for co-simulation with external tools [10] that would have enabled a coordinated simulation of the power grid in PowerFactory and the heat pump in Dymola. However, co-simulation of PowerFactory with Dymola was not performed, as in the grid simulation each heat pump would have needed one separate instance of Dymola. Hence, the simulation of a complete low voltage grid with dozens of heat pumps would be limited by technical constraints. Therefore, a simplified model of the heat pump was created in PowerFactory that enables the combined simulation of the power grid and the heat pump considering the customers comfort zones within one simulation tool without needing a co-simulation environment. This model is described in section 2.2 and it is validated in section 2.2.1.

2.2. Heat pump model

A simplified heat pump model was developed that incorporates the thermal characteristics of the building and the hot water buffer. With this model, it is possible to draw conclusions on the thermal comfort zones of the customer by modelling the thermal storage, the heat capacity of the building and the hot water tank. These thermal buffers are summarised in one linear storage with a specific capacity. As a result, a state of charge (SoC) of zero means that the temperatures of all comfort zones have reached the thermal lower limit given by the customer (e.g. 55°C minimal hot water temperature). A SoC of 1 means that the temperatures of all comfort zones have reached the thermal upper limit that is acceptable by the customer (e.g. 80°C maximal hot water temperature). The simplified model is described in detail in [11] and its characteristics are shown in Table 1.

2.2.1. Validation of the model

The simulation results of the simplified load model were compared with the simulation results of the Dymola model to validate the comparability of the models as shown in Fig. 1.

The validation of the simplified model in terms of operation frequency, operational hours and energy consumption showed that the simplified PowerFactory model has similar behavior like the detailed Dymola model. The simplified model has an insignificant higher energy consumption than the detailed model, meaning that the simulation results show a worst case assumption within the given heat pump penetration scenarios. More details about the validation of the models can be found in [11].

Table 1. Constraints of the simplified heat pump model [11]

	Real heat pump / Dymola model	Simplified heat pump / PowerFactory model
Thermal power	Variable	Constant
Electrical power	Variable	Constant
Coefficient of Performance	Variable	Constant
Thermal buffer behavior	Non-linear	Linear
Power-on peaks	Depending on the type	None

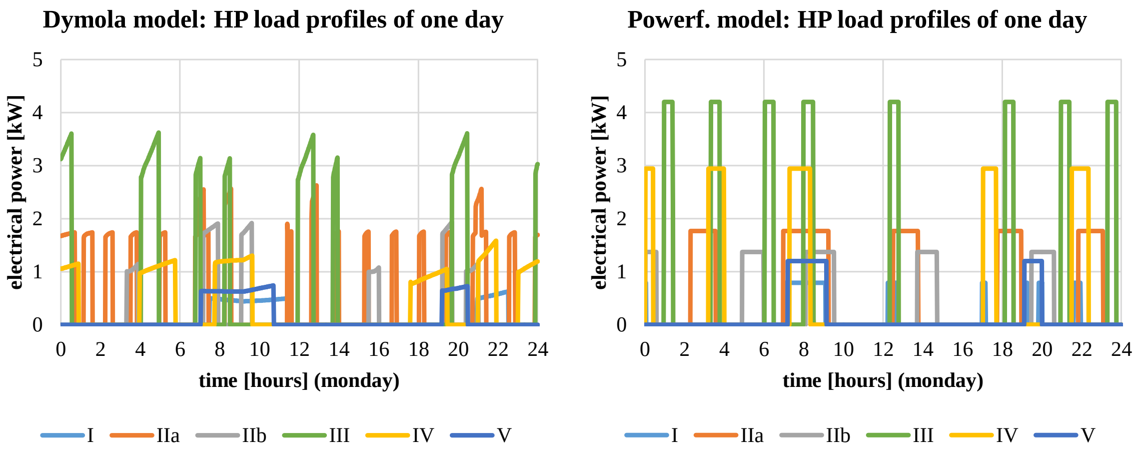

Fig. 1. Power Profiles of heat pump operation in the Dymola model (left) and the PowerFactory model (right) [11]

3. Analysed Case Studies

3.1. Grid models

The characteristics of the three Austrian LV grids analysed within this work are shown in Table 2. Grid A is a typical rural network with a rather high areal spread of the customers. Grid B is the most urban grid of all with 100% underground cabling degree, although it is still classified as rural grid. Grid C is the most rural grid with mostly farmers connected in a very high areal spread.

Table 2. Characteristics of the case study grids

	Grid characteristic	Grid A	Grid B	Grid C
Transformer	Nominal power	630 kVA	250 kVA	250 kVA
Branches	Number	11	6	4
	Length	750 m	640 m	1100 m
Loads	Buildings	165	95	54
	Customers	173	127	28
	Households	150	99	8
PV	Systems installed	56	46	17
	Total Power	330 kWp	195 kWp	135 kWp

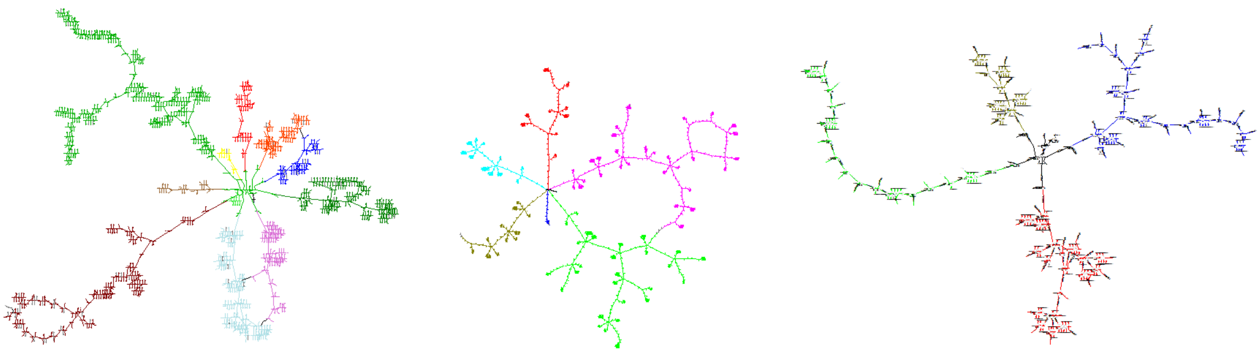

Fig. 2. Case study grids: Grid A (left), grid B (middle), grid C (right); logical topology is shown, not geographical

3.2. Heat pump types and their penetration

Within the iWPPflex project, characteristics for several types of heat pumps that are common in Austria were elaborated. The characteristics are shown in Table 3.

The heat pumps were assigned to the buildings in the case study grids according to Table 4, although not all heat pumps were used in simulations depending on the heat pump penetration scenarios.

Table 3. Characteristics for heat pump types common in Austria [2]

	CASE I: Passive House	CASE IIa: New Building	CASE IIb: New Building	CASE III: Existing Building	CASE IV: Existing Building, ren.	CASE V: DHW-HP
Space Heating	15 kWh/(m²a)	45 kWh/(m²a)	45 kWh/(m²a)	100 kWh/(m²a)	70 kWh/(m²a)	-
	[~30 °C]	[~35 °C]	[~35 °C]	[~55 °C]	[~45 °C]	
Heated area	140 m²	140 m²	140 m²	120 m²	120 m²	-
DHW	3000 kWh/a	3000 kWh/a	3000 kWh/a	3000 kWh/a	3000 kWh/a	3000 kWh/a
	[~55 °C]	[~55 °C]	[~55 °C]	[~55 °C]	[~55 °C]	[~55 °C]
Therm./ el. capacity	3 kW / 1 kW	5 kW / 1.5 kW	5 kW / 1.2 kW	12 kW / 4 kW	7 kW / 2.7 kW	2 kW / 0.7 kW
Capacity control	variable	on/off	on/off	on/off	variable	on/off
Heat Source	Air	Air	Ground	Ground	Air	Air

Heat Sink	Water	Water	Water	Water	Water	Water
Heat Distribution	Floor Heating	Floor Heating	Floor Heating	Radiators	Radiators	-
Storage SH	no	300 l	no	500 l	500 l	-
Storage DHW	300 l	300 l	300 l	300 l	300 l	250 l

3.3. Simulation setup

3.3.1. Heat pump penetration

In the different heat pump penetration scenarios, either 30%, 40% or 50% of the existing households were equipped with heat pumps, see Table 4 and Table 5. In the reference scenario no additional heat pumps are included in the grid, but power profiles incorporate the usage of electric water heaters.

Table 4. Heat pump penetration in case study grids (for 50% penetration scenario)

Network	I	IIa	IIb	III	IV	V	Total
Grid A	6	14	15	11	32	5	83
Grid B	4	8	3	9	12	10	46
Grid C	2	1	3	0	7	0	13

Table 5. Total heat pump connection power for the different heat pump penetration scenarios compared to transformer peak load

Network (peak load)	30%	40%	50%
Grid A (290 kW)	88 kW	159 kW	196 kW
Grid B (160 kW)	65 kW	84 kW	104 kW
Grid C (80 kW)	25 kW	28 kW	37 kW

3.3.2. Load profiles

Realistic power profiles for the three grids were available only for selected typical days in the year, meaning three days for summer and winter, each containing one weekday (valid for Monday to Thursday), one Friday (valid also for Saturday), and one Sunday (valid also for public holidays). The combination of high grid-load with low PV infeed (bad weather conditions) brings the grids the closest to their limits. Therefore, the simulation of winter days is sufficient for analyzing the impact of high heat pump penetrations on the grid, because grid loading as well as heat pump demand is higher in winter than in summer. Since power flows are very fluctuating in low voltage grids, voltage situations in the grid can differ significantly from day to day. Therefore, an investigation of only three days would lead to rather insignificant results. To increase the significance of the results, load profiles of all customers in the grids were permuted on the one hand, and phase connections of the three-phase power profiles at each customer were also permuted on the other hand. This variation was performed three times for load profiles and three times for phase connections. These nine variants of each simulated day significantly increase the diversity of the analyzed grid situations. The results discussed in chapter 4 will show an extrapolated week containing four times weekday, two times Friday and once Sunday in all nine variants.

3.4. Heat pump operation strategies

The following heat pump operation strategies were investigated:

3.4.1. Conventional, autonomous and independent heat pump operation

In this scenario, all heat pumps act according to their local thermal heat pump control without any external signal. According to the model, the heat pump starts operation as soon as the thermal buffer reaches the given lower limit and stops operation when the thermal buffer reaches the given upper limit. The relation between on and off time depends on the heat demand from the building.

3.4.2. Grid friendly control via blocking times

In this scenario, the DSO can define one or more timespans per day of usually one hour, where all heat pumps that participate in this control are set inactive. Usually, the blocking times are fixed every day, but also dynamic blocking hours can make sense to react on peak demand. Depending on the individual characteristics of the grid, blocking hours can be meaningful during midday (lunchtime peaks are most common in the majority of LV grids due to cooking) and / or in the evening, but in principle also load peaks in the morning can be avoided. Since heat pumps are not allowed to turn on during blocking times, a violation of the customers comfort zones might occur if the household's heat demand is high during blocking times or if the heat pump's thermal buffer level was low when entering blocking time. Therefore an optimized grid controlled operation was also simulated, where the heat pump brings its thermal buffer level close to the maximum before blocking time starts. In this optimized simulation, customer's comfort zones do not get violated within the blocking hour and also a high coincidence factor of heat pump operation at the end of the blocking times will be avoided.

3.4.3. Market participation via arbitrage

In this scenario, heat pump operation is optimized to be in operation in times where energy price is low. In contrast to the previous scenario, the customer's comfort has highest priority, meaning that the heat pump will turn on regardless the current energy price if the energy buffers are empty. Due to the fact prices for electric energy are equal for all customers in the grid, the on/off behavior of heat pumps following arbitrage optimization can significantly increase the coincidence factor of the heat pumps in the whole grid. For these simulations, day-ahead prices from the EPEX Spot marked [12] were used from the third January week 2014.

The arbitrage behavior of the heat pumps was modeled through adjusting the heat pump's lower limit for starting operation when the buffer is empty as well as adjusting the heat pump's upper limit for stopping operation when the buffer is full. In the analyzed case studies, the lower limit was increased to 50% state of charge in times of low prices, and on the contrary, the upper limit was decreased to 50% state of charge in times of high energy prices. Both actions narrow the heat pump's thermal buffer leading to an increase in on/off cycles, but customer's comfort will not be violated.

4. Simulation Results

4.1. Impact of heat pump penetrations in conventional independent operation on the grid

The impact of the analyzed heat pump penetration scenarios on grid voltage is shown in Fig. 3, the impact on line loadings in Fig. 4 (hp00… without heat pumps, hp30/40/50… 30%, 40% and 50% heat pump penetration). In both figures, boxplots show the variation of the investigated extremal values for all nine variations of load profiles and phase assignments that were simulated for three typical days (workday, Friday, Sunday) of one week in winter and extrapolated to one week.

As expected, in all three grids the lowest grid voltage decreases by the increase of the number of heat pumps in the grid. While grid B is far away from any voltage or line loading limit, grid A and C show voltage violations in the heat pump penetration scenarios, but line loading is not critical.

In grid A combinations of load profile variation and phase permutation exists were even in the reference scenario without heat pumps the voltage limit of 90% [13] is violated. This is reasoned in the facts that the load profiles used have a rather high coincidence factor to consider worst-case situations, and furthermore cold winter days were analyzed were load is high. Accordingly, the grid can be considered to be near its capacity limit and the integration of further loads like heat pumps would require reinforcement of some lines on the critical branches. This is also confirmed by the analysis of the line loadings that come close to 100% at 50% heat pump penetration level, at least in one variation scenario.

Furthermore, in grid C 50% of the simulated variations are near or below the 90% voltage limit in reference scenario without heat pumps. This is reasoned in the circumstance that this grid is the most rural grid with a big geographical supply area and only few customers that are mainly farmers with high agricultural loads. To consider worst case scenarios, also in this grid high coincidence of loads was assumed. It must be stressed that the boxplots only show the variation of the minimal 10min average of grid voltages of one week for the nine load- and phase-permutations. Therefore the analysis presented here is not optimal for making general statements about the state of the grid and the necessity for reinforcement.

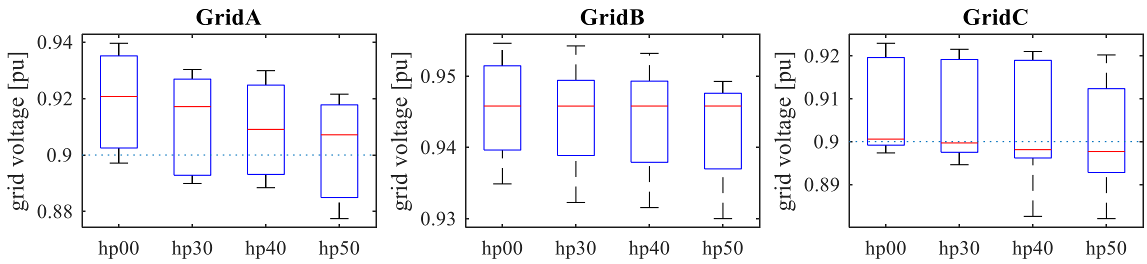

Fig. 3. Variation of the lowest grid voltage (10min avg. value) for the investigated heat pump penetration scenarios in the analyzed grids. Note: the boxplots are not representing the voltage distribution, but used for the purpose to show different levels of the *minimum* voltage.

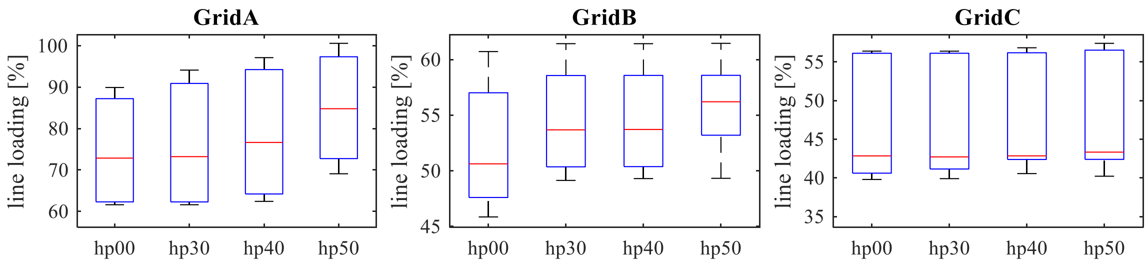

Fig. 4. Variation of the highest line loadings (10min avg. value) for the investigated heat pump penetration scenarios in the analyzed grids. Note: the boxplots are not representing line loading distribution, but used for the purpose to show different levels of *maximal* line loading.

4.2. Impact of the investigated heat pump operation strategies on the grid

Fig. 5, Fig. 6 and Fig. 7 show the impact of the investigated heat pump operation strategies on the grid voltage by visualizing the variation of the lowest voltage in the grid the same way as in Fig. 3 (the boxplots labeled by 'w.o. hp', 'hp30 ref', 'hp40 ref' and 'hp50 ref' in the figures below correspond to 'hp00', 'hp30', 'hp40', and 'hp50' shown in Fig. 3). For each heat pump penetration scenario (hp30, hp40 and hp50), a group of boxplots show the lowest grid voltage for each heat pump operation strategy

The lower part of each figure shows the impact of the operational strategies on the heat pump operation coincidence factor. In this diagram, zero means all heat pumps are off, while one means all heat pumps are in operation at the same time.

Grid A and B have a significant number of heat pumps installed in the penetration scenarios, therefore the coincidence factor is below 0.8 in the reference scenario apart from one outlier in both grids were it is nearly one. Grid C is the smallest grid with only few heat pumps, therefore the coincidence factors that occurred are in general higher and there are several times where (nearly) all heat pumps are in operation.

As expected, the higher the heat pump penetration is, the lower the maximal coincidence factors get, even if the effect is not very big.

Surprisingly, results show that blocking times do not have a significant positive impact on the lowest grid voltage in this analysis. This is reasoned in the fact that at the end of the blocking times many heat pumps start refilling their thermal buffers at the same time which weakens the effect of the blocking times. Furthermore, in these simulations the blocking times were not dynamically set according to the actual grid loading. Instead, they were set statically according to typical schedules of Austrian DSOs. Results showed that in the analyzed grids the occurred peak load times did not exactly fit these schedules, meaning that the times where heat pumps were off did not fully cover the times with the lowest grid voltages.

In contrast to this, simulation results show that the optimized operation of heat pumps prior to blocking times has a positive impact on the lowest grid voltages in nearly all cases – though the effect is not very big. With an optimal load shifting it could be possible to shift heat pump operation completely away from the times with the lowest grid voltages to bring back the level of the lowest grid voltage to the level without heat pump operation. This was not realizable with the investigated operational strategies with blocking times.

In grid A and grid B, market operation of heat pumps has a negative impact on the lowest grid voltages, even if the effect is not that significant. Surprisingly, in grid C market operation has a positive impact on grid voltages. This can be reasoned by the fact that this grid is small with only a few heat pumps, and positive effects by coincidence are much more likely than in the bigger grids. In this case, the combination of the load profiles used for simulations within this grid and the used market signals coincidentally have a positive effect on the lowest grid voltage. This is also the case in some variation scenarios in grid A, were on the one hand market participation leads to the lowest grid voltages, but on the other hand the 100% percentile of the boxplots shows a significant improvement in grid voltage – meaning that the spread of possible impacts on the grid increases.

Furthermore, it is interesting to see that in general the highest coincidence factors decrease in the optimized blocking time and the market scenario compared to the autonomous and the non-optimized blocking time scenario. It is assumed that this might be a result of the initial conditions for the simulations where it was chosen to start all heat pumps with a 'state of charge' of the thermal buffer of 50%, while one half of the heat pumps start in operation and the other half are off. In retrospect, these starting conditions are not realistic and should be improved in further simulations.

The expected effect that marked participation increases coincidence factors was not that high as assumed. The highest increase occurred in grid A when considering the median and the 75% percentile, while in grid B the 75% percentile of the coincidence factor is even lower than in the autonomous operation. Again, this might be an indication that the simulation setup of the reference scenario might lead to too high coincidence factors.

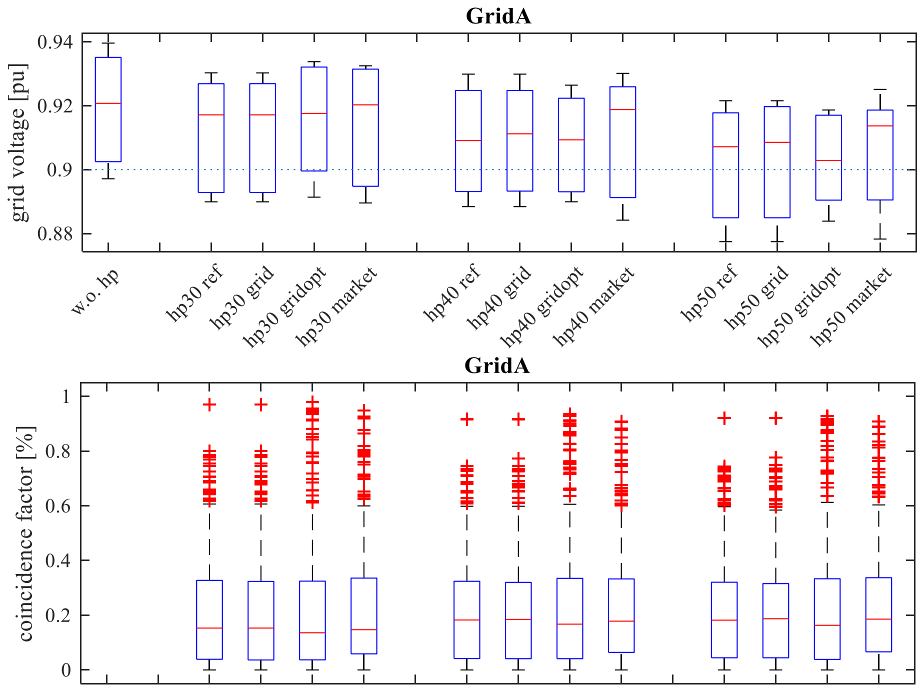

Fig. 5. Impact of the investigated HP operation strategies on grid voltage (above) and corresponding coincidence factors (below) for Grid A

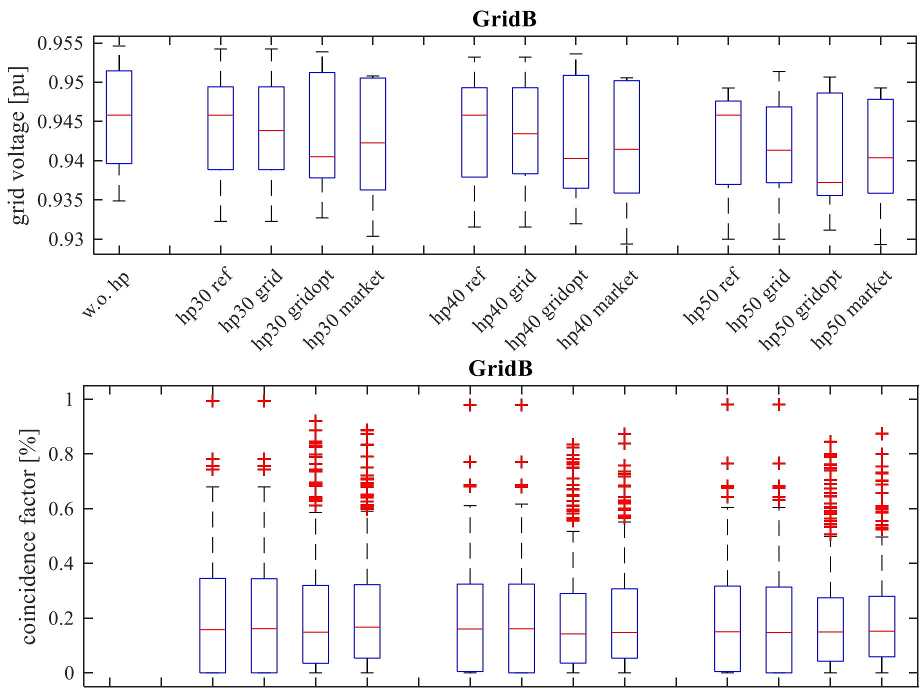

Fig. 6. Impact of the investigated HP operation strategies on grid voltage (above) and corresponding coincidence factors (below) for Grid B

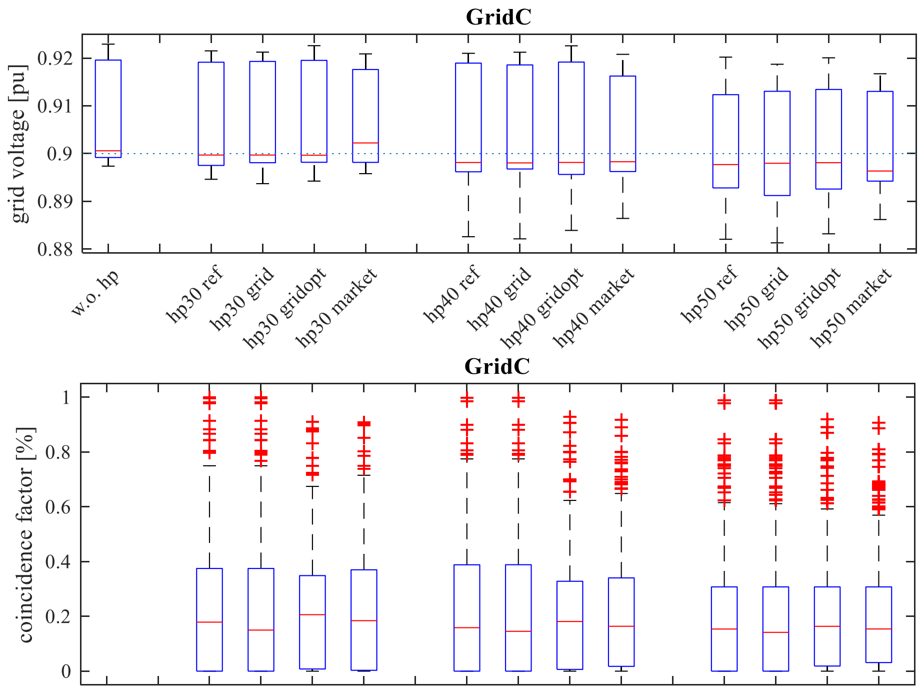

Fig. 7. Impact of the investigated HP operation strategies on grid voltage (above) and corresponding coincidence factors (below) for Grid C

4.3. Summary

The results for the analyzed case study grids can be summarized as follows:

- A heat pump penetration of 50% decreased the lowest voltage in the grid by 0.5 to 2% while the maximal line loading is increased by up to 10%.
- Even in the 50% penetration scenario, the predominant causes of high voltage drops are the ordinary loads and not the heat pumps in all three grids. On the one hand, this is reasoned in the fact that heat pumps are

all modelled as three-phase symmetrical loads that have much less impact on grid voltages than single-phase loads. On the other hand, load profiles used for simulations cover worst case power flow situations.

- The operation strategy with blocking times could not compensate the impact of the heat pumps on the lowest grid voltage due to the fact that times of high grid loading did not fully match the blocking times and the fact that after the blocking times a high coincidence factor of heat pump operation was observed because thermal buffers were empty. When heat pumps increase their thermal buffer level prior to blocking times, a positive impact on grid voltage was observed in general, although the effect was not very significant.
- The expected increase in coincidence factors due to market participation of heat pumps and a resulting negative impact on grid voltages was not observed in all grids. Of course this can be reasoned in the fact that a heat pump that has already filled its thermal buffer cannot stay in operation any more even if prices are low, and on the other hand a heat pump that has emptied the thermal buffer needs to go in operation even if prices are high. Nevertheless, it is assumed that minor weaknesses in the simulation initial conditions as well as the quite short observation time period of only three days can also be the reason for that phenomenon.
- The median of the coincidence factors of heat pump operation lies slightly below 0.2, and the 75% percentile is between 0.3 and 0.4 in all simulated scenarios. In nearly all simulated scenarios, the highest coincidence factor lies above 0.9 while the operation of 100% of the heat pumps only occurs in cases with few heat pumps (30% penetration in grid B, 30% and 40% penetration in grid C).

5. Conclusion and Outlook

This paper discussed the impact of high heat pump penetrations and different heat pump operation strategies on the low voltage grid. Therefore, power flow simulations were performed for three Austrian case study grids were heat pumps at 30, 40 and 50% of all houses in the grid were assumed. A simplified heat pump model based on a linear storage was developed and directly integrated into the power grid simulation software to be able to simulate the behavior of dozens of heat pumps in parallel to the electrical grid. Four different heat pump operation scenarios were investigated: Independent and autonomous heat pump operation, heat pump operation with blocking times to relieve the low voltage grid in times of high load, an optimized heat pump operation with blocking times and marked operation.

The case studies of three Austrian low voltage grids showed that the impact of heat pump installations for space heating and hot water at 50% of the buildings in the grid is lower than expected. Grid constraints are violated in two of the three grids, but these grids were very close to their capacity limits also without heat pumps. In all three grids, the predominant causes of high voltage drops are the ordinary loads and not the heat pumps.

Simulations showed that the introduction of blocking hours does not bring significant relieve to the grid – at least when considering the lowest grid voltage, but a combination with a pre-charging of the heat pumps thermal buffer prior to the blocking hours brings insignificant improvements in the analyzed case studies. It is expected that a dynamic setting of the blocking hours according to the actual grid loading will further improve the situation in the grid.

The expected negative impact of day-ahead spot market operation on the grids was observed only to some extent. The analysis of this phenomenon leads to the conclusion that simulation results highly depend on the assumed boundary conditions, on the load profiles and other simulation input parameters as well as the observed time periods. All in all, the analysis of extremal values of voltages (or line loadings) is difficult because these extremal values occur very seldom and highly depend on the interplay of all simulation parameters. Nevertheless, according to the European standard EN50160 [13], especially the 5% percentile of the 10min average value of grid voltages have to be above 90% of nominal voltage and the lowest 10min average value of grid voltages has to be within 85% of nominal voltage.

It must be stressed that the case studies presented here only show the behavior of three grids in a time frame of one week and therefore results cannot be generalized and no generalized conclusions can be drawn.

As a consequence, simulations will be performed for a longer time period to get more accurate results on market participation. High attention will be paid on the diversity of the used load and thermal demand profiles to achieve a good representation of situations in real grids. Furthermore it will be analyzed in how far flexible blocking times can improve voltage impact of heat pumps on the grid or if other improvements of the heat pump operation strategies will lead to better results concerning the occurrence of the lowest grid voltages. Finally, it is planned to extend the developed heat pump model by a variable coefficient of performance that depends on the heat pumps thermal buffer level to be able to obtain results about heat pump efficiency.

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