VOLTAGE SUPPORT IN DISTRIBUTION GRIDS USING HEAT PUMPS

Marc BRUNNER
University of Stuttgart – Germany
marc.brunner@ieh.uni-stuttgart.de

Krzysztof RUDION
University of Stuttgart – Germany
rudion@ieh.uni-stuttgart.de

Stefan TENBOHLEN
University of Stuttgart - Germany
stefan.tenbohlen@ieh.uni-stuttgart.de

ABSTRACT

This paper investigates the potential of heat pumps to increase the self-consumption of households and to lower the occurring voltage rise within a low voltage distribution grid due to a high photovoltaic (PV) infeed. An electrical-thermal simulation model is applied as basis to perform this investigation. As the thermal demand of households varies drastically during the year, the focus lies on a monthly comparison of the results. The thermal demand for hot water is considered additionally. Results imply that heat pumps are able to increase the self-consumption, to reduce the maximum grid infeed from PV and to minimize the voltage rise caused by a high PV infeed. A comparison of different seasons revealed that even throughout the summer there are some substantial effects regarding the reduction of the maximum PV-infeed and the maximum voltage, although the effects were highest throughout the winter and the transitional period. This indicates that the thermal demand for hot water enables heat pumps to participate in future demand-side management even throughout summer. This is also relevant for future scenarios with new buildings and only little thermal demand for space heating, as in these buildings the thermal demand for hot water represents an important fraction of the overall thermal demand throughout the entire year.

INTRODUCTION

The energy demand for space heating and warm water of private households exceeds 80% of the end energy consumption of private households and more than 20% of the entire end energy consumption of Germany [1]. Due to thermal heat storages and thermal masses of buildings, the instantaneous generation of heat does not necessarily have to match its demand continuously. Hence, if only a fraction of the thermal energy demand is covered electrically, e.g. by heat pumps (HP), the aforementioned possibility to decouple heat generation and heat demand can be used to support the operation of the electrical power grid, e.g. to optimize the voltage level in low voltage grids influenced by a high infeed of photovoltaic generation systems (PV).

While taking part in the process of voltage optimization, the heat pump still has to cover the thermal demand reliably. Thus, if there is no thermal demand at all, it will not be possible to operate the heat pump and therefore to perform demand-side management. As there is almost no thermal demand for space heating throughout the summer period, this work especially incorporates the thermal demand for hot water. In contrary to the energy demand for space heating the thermal demand for hot water for private households is approximately evenly distributed throughout the year.

Figure 1 demonstrates the electric energy production by a PV unit and the thermal energy demand for space heating and hot water.

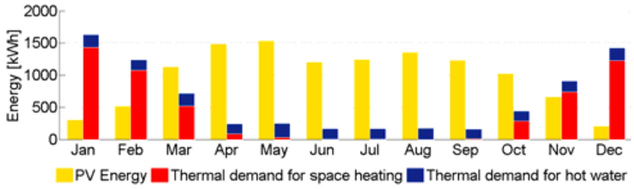

Figure 1: Electric energy production by a PV unit and thermal energy demand for space heating and hot water for an exemplary household

It can be clearly seen that only for the transitional periods a thermal demand coincides with a notable infeed from PV. Furthermore, it becomes observable that the thermal demand for hot water is almost constant but – compared to the thermal demand for space heating during winter – at a significantly lower level.

In the past, some work has been performed investigating the ability of heat pumps for demand-side management [2] – [11]. Whereas some investigations are seeking to lower the residual load [2] – [4], others are trying to maximize the self-consumption of heat pumps by shifting their times of operations into times of a high photovoltaic infeed. The authors in [5] showed, that the self-consumption can reach levels between 55% and 65% due to the consideration of heat pumps. [6] finds that heat pump systems are able to follow the PV infeed. The authors in [7] find that the combination of heat pumps and electric vehicles are suitable to better integrate PV into the grid with an appropriate control. [8] – [11] are additionally investigating the effects of heat pumps on the voltage level.

This paper applies an alternative approach and especially incorporates the thermal demand for hot water. Beside the potential to rise self-consumption, the impact of this increased self-consumption on a low voltage power grid is estimated by performing load flow calculations.

OBJECTIVE OF PAPER

The objective of this paper is to investigate whether heat pumps are capable to shift their operation to times of a high PV infeed. The focus lies on the additional consideration of hot water and the effects of different seasons on these capabilities. To do so, the corresponding self-consumption is investigated.

Secondly, the effects of such an optimized self-consumption on low voltage distribution grids are investigated. The subject addressed is whether heat pumps are suitable to lower a PV-induced voltage rise.

METHODOLOGY

General Approach

In order to investigate the above mentioned subject, a complex simulation model is applied ([12] – [14]). The model is able to simultaneously compute the thermal and electrical parameters of households as well as the electrical parameters of the low voltage power grid.

Within the simulation, a certain amount of households is equipped with heat pumps. Two modes of operation of the heat pumps are being compared:

- a heat-driven mode of operation and a
- control for an optimized self-consumption.

The model simulates every household with the corresponding heat pumps simultaneously. A quasi-stationary load flow calculation with a time step of 15 minutes is performed in order to assess the impact of heat pumps on the voltage level.

In order to assess these impacts, one exemplary household is analysed in a first step. In a second step, this methodology is applied to several households and the grid-wide impacts are investigated.

Model Description

An overview of the basic functionality of the model applied is given in Figure 2 and has previously been published ([12], [13], [14]).

The model consists of a thermal and an electrical submodule. Within the electrical submodule the control determines, whether the corresponding heat pump is switched on or off. In order to do so, the actual temperature of the heat storage is considered. Eventually, based on the type of control, the PV infeed is additionally taken into account. This is done to maximize the self-consumption. If the control determined to switch on the heat pumps, the coefficient of performance (COP) and other thermal parameters are computed within the thermal submodule (e.g. the temperature and the actual thermal losses of the heat storage), which in turn influences the electrical submodule.

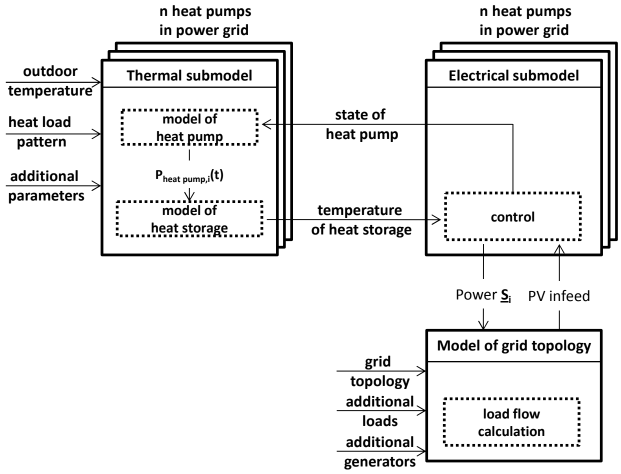

Figure 2: Basic functionality of the electrical-thermal model applied within this paper

The electrical power consumption of each heat pump is then considered by an electrical load flow calculation. The load flow calculation also considers the other loads and generators within the actual low voltage power grid additionally.

The modelling of the heat pump and the thermal heat storage are described in more in detail in [12]. The heat pumps are assumed to be air-water heat pumps and are operated continuously between 10% and 100% of their corresponding nominal thermal power. Each heat pump is equipped with an additional non-electrical heater to cover the peak thermal loads during the coldest days in winter. According to DIN EN 15450 [15] the thermal energy provided by the additional peak load heater provides 2% of the annual thermal energy demand of the corresponding private household. The hot water profiles are derived from the publicly available software DHWcalc [16]. The average yearly thermal demand for hot water is assumed to be approximately 530 kWh_{th} per person [15].

The electrical power grid represents a typical low voltage power grid in Germany. It consists of approximately 70 households. The PV data is based on real measurements of a 1020 W_p module set up in Stuttgart, Germany. It is assumed, that every household equipped with a PV unit also contains a heat pump. Every PV unit is simulated with an installed peak power of 10 kW_p. In addition to these, no further PV units are considered. This in turn means that the results with respect to a potential reduction of a PV-induced voltage rise constitute theoretical potentials, as this assumption represents a best-case scenario for voltage reduction.

The specific thermal demands of the considered buildings are between 50 – 100 $\frac{kWh}{m^2 \cdot a}$, the conditioned area ranges from 110 m^2 to 240 m^2. The heat storage within the buildings is assumed to have a specific heat capacity of 200 $\frac{liters}{kW_{th}}$ and additionally 200 litres for the consideration of hot water.

Control of the Heat Pumps

Heat-driven Mode of Operation

The heat-driven mode of operation ensures that the heat storage has a constant temperature of 55° Celsius. If the temperature falls below or rises above this level, a P-controller rises or lowers the heating power of the heat pump correspondingly.

Control to Maximize Self-Consumption

This mode of operation aims at optimizing the self-consumption.

In a first step, the heat demand and the PV infeed are compared. Both are assumed to be perfectly forecasted. In this step, the operation scheme of the heat pump is planned to exactly follow the PV infeed when the infeed is at its maximum. This is done until the thermal energy demand (assuming a constant COP) is theoretically covered. At all other times, the heat pump is assumed to be switched off.

As this target profile obviously does not incorporate the restrictions given by the maximum and minimum capacity of the heat storage and thus does not cover the thermal demand reliably, a constrained least-square optimization with a time horizon of 24 hours is applied in a second step:

$$\min \sum_{i=1}^{96} \left(P_{th,i} - target_i\right)^2 \quad (1)$$

subject to

$\forall n \in [1, 96]$:

$$\mathrm{E}_{\mathrm{th,min}} \leq \sum_{i=1}^{n} (P_{th,i} - demand_i) \cdot \Delta t \leq \mathrm{E}_{\mathrm{th,max}} \quad (2)$$

$\wedge \forall i \in [1, 96]$:

$$0 \leq P_{th,i} \leq P_{th,max} \quad (3)$$

In which $P_{th,i}$ reflects the thermal power of the heat pump in time step i and $target_i$ is the calculated thermal load profile resulting from step 1. $E_{th,min}$ / $E_{th,max}$ refer to the minimum / maximum capacity of the heat storage and $demand_i$ refers to the thermal load. Δt is assumed to be 15 minutes. In other words, step 2 ensures that the heat pump follows the targeted profile as close as possible but with the additional consideration of thermal restrictions.

As heat pumps are having a minimum thermal load $\mathrm{P}_{\mathrm{th,min}} > 0$, equation (3) violates this by accepting solutions in $(0, P_{th,min})$. This is done for reasons of computational time and is corrected in a third step: the state-of-charge (soc) of the thermal storage is computed for every time step:

$\forall n \in [1, 96]$:

$$soc_{optim,n} = soc_{t=0} + \frac{\sum_{i=1}^{n} \left(P_{th,i} - demand_i - loss\right) \cdot \Delta t}{E_{th,max}} \quad (4)$$

whereas $soc_{optim,i}$ refers to the computed state-of-charge from the optimization problem at time step i, *loss* refers to an estimated mean thermal loss of the heat storage per time step and $soc_{t=0}$ refers to the initial state-of-charge.

The simulation is carried out by applying the computed optimal operation of the heat pump (see Equation (1)), resulting in different storage temperatures for every time step. Based on these temperatures, a soc is defined:

$$soc_{sim} = \frac{\vartheta_{storage} - 45°\,C.}{15°\,C.}, \quad \vartheta_{storage} \in [45, 60] \quad (5)$$

Finally, if $P_{th,i}$ is computed to be in $(0, P_{th,min})$, equation (6) finally sets $P_{th,i}$ to its valid set $\{0 \cup [P_{th,min}, P_{th,max}]\}$:

$$P_{th,i} = \begin{cases} 0, & if\ soc_{sim,i} > soc_{optim,i} \\ P_{th,min}, & if\ soc_{sim,i} \leq soc_{optim,i} \end{cases} \quad (6)$$

RESULTS

The approach to demonstrate the voltage stabilization effect of heat pumps due to an optimized electrical self-consumption is based on three steps: in a first step, the self-consumption throughout the year for one exemplary household is shown. In a second step, the effect of the increased self-consumption is demonstrated by illustrating the changes to the power injection to the grid (neglecting other electrical consumers within the household) due to the different control schemes. In a third step, a low voltage grid is simulated assuming that all the heat pumps installed in the low voltage grid are operated with the same mode of operation (heat-driven or control for an optimized self-consumption).

Self-Consumption and PV Infeed of an Exemplary Household

Self-Consumption

For an exemplary household, Figure 3 shows the share of the produced PV energy instantaneously consumed by the heat pump. For each month, 2 bars are shown. The left bar shows the results for the heat-driven mode of operation, the bar to the right indicates the results for the control maximizing the self-consumption of the household.

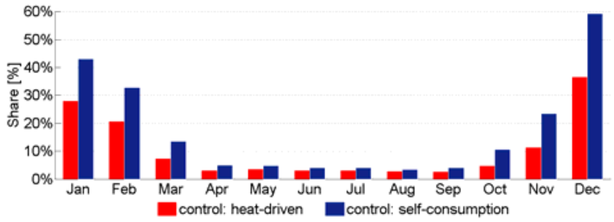

Figure 3: Monthly analysis of self-consumption for an exemplary household (left bar: heat-driven, right bar: control for a maximized self-consumption)

The self-consumptions shown in Figure 3 only consider the electricity demand of the heat pump and do not consider the remaining electrical loads of the household (e.g. for lighting or other electronic devices) as they are assumed to be not controllable. Simulation results show that, for instance, the heat-driven mode of operation already reaches a share of self-consumption of approximately 35% in December. This share of self-consumption increases by over 20% to almost 60% by applying the control for an optimized self-consumption. The very low share of self-consumption between April and September can be explained by the high PV energy produced on the one hand side and the declining thermal energy demand during the summer months on the other.

Impact on PV Infeed of Exemplary Household

As the control for an optimized self-consumption aims at operating the heat pump when the power provision of the PV unit is at its peak, the resulting power infeed to the low voltage grid is lowered consequently. But even for the heat-driven mode of operation, which neglects the PV infeed, a certain reduction of the grid infeed is likely as the operation of the heat pumps sometimes coincides with a high PV infeed coincidently. Figure 4 shows the absolute maxima and the 99^{th} percentile of the power infeed to the grid. In Figure 4, the remaining electrical loads (e.g. for lighting or electronic devices) are neglected as they are assumed to be constant.

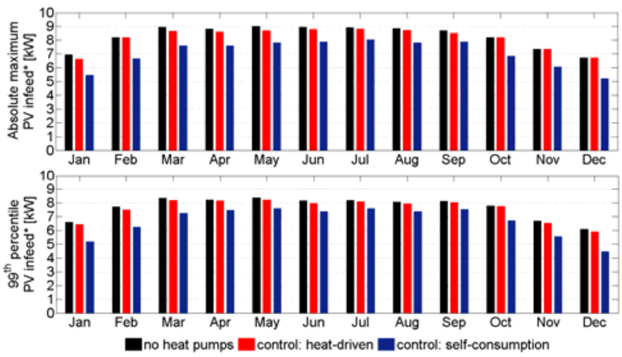

Figure 4: Absolute maxima and 99^{th} percentiles of the sum of the PV power and the power demand of the heat pump (*: PV infeed without remaining load of household)

Although the reduction is higher throughout the winter period, it can be noticed, that the heat pump in the exemplary household can reduce the maximum PV infeed even throughout summer, when there is almost no thermal demand for space heating. This indicates that the thermal demand for warm water is sufficient to influence the grid at a notable level throughout the entire year.

Effect on Voltage Due to Self-Consumption

This section demonstrates the effects of the previously shown control scheme on an exemplary low voltage power grid, assuming that every heat pump operated within the grid is controlled with the same mode of operation (heat-driven or optimized self-consumption, respectively). Figure 5 illustrates the effects on a low voltage distribution grid over one year. The outliers indicate the absolute maxima respectively the absolute minima, the antennas indicate the 99.9^{th} respectively 0.1^{st} percentiles and the lower and upper edges of the box show the 95^{th} respectively 5^{th} percentiles of all appearing voltages within the grid during one specific month. The 50^{th} percentiles are shown within the box.

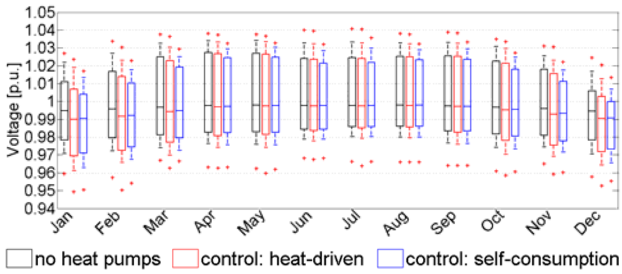

Figure 5: Results of load flow simulation for a penetration rate of heat pumps equal to 20%

It can be clearly seen that the control to optimize the self-consumption lowers the voltage rise caused by the PV infeed. This can be explained by a reduced maximum PV infeed, as shown in Figure 4 for one exemplary household. It is noteworthy, that even throughout the summer period there is some potential to influence the grid in a suitable way. As there is almost no heat demand for space heating throughout summer, this also indicates that the thermal energy demand for hot water is sufficient to provide some voltage support.

CONCLUSION

This paper showed the effects of heat pumps on a typical low voltage distribution grid by applying a pre-existing electrical-thermal simulation model. Two modes of operation of the heat pumps were compared: a so-called heat-driven mode of operation and a control aiming at maximizing the self-consumption of the corresponding households. It was shown for an exemplary household that the share of self-consumption rises from less than 40% to almost approximately 60% in December with an appropriate control. Furthermore, it was shown that this led to a reduced PV infeed of that household into the power grid. Assuming this mode of operation being applied to every household equipped with a heat pump, load flow calculations showed furthermore reductions of the PV-induced voltage rise. For the summer months, simulations revealed that the thermal demand for hot water is also enough to provide some stabilizing effects on the low voltage grid. This becomes especially noteworthy, as the better thermal insulation of future buildings will lead to a lower overall thermal demand. This in turn makes the thermal demand for hot water an important factor for the ability of heat pumps to participate in future demand-side management.

MISCELLANEOUS

Acknowledgments

We thank the German Ministry of Science, Research and the Arts Baden-Württemberg for funding the project "Dynamic simulation and optimization of decentralized energy concepts". We would also like to thank the Institute for Photovoltaics at the University of Stuttgart, Germany for the provision of measurement data.

REFERENCES

[1] AG Energiebilanzen e.V. (2013). Anwendungsbilanzen für die Endenergiesektoren in Deutschland in den Jahren 2011 und 2012 mit Zeitreihen von 2008 bis 2012, Berlin, November 2013.

[2] Toersche, Bakker, Molderink, Nykamp, Hurink, Smit (2012). Controlling the heating mode of heat pumps with the TRIANA three step methodology. Proceedings of 2012 IEEE PES Conference on Innovative Smart Grid Technologies, Washington D.C./USA.

[3] Tanaka, Yoza, Ogimi, Yona, Senjyu, Funabashi, Kim (2012). Optimal operation of DC smart house system by controllable loads based on smart grid topology. Renewable Energy 39.1 (2012), pp. 132-139.

[4] Spitalny, Diekerhof, Myrzik (2012). Potential und Effizienzbetrachtung beim Lastmanagement von Wärmepumpen im Sektor der privaten Haushalte. Konferenz für nachhaltige Energieversorgung und Integraion von Speichern NEIS 2013, Hamburg.

[5] Williams, Binder, Kelm (2012). Demand Side Management through Heat Pumps, Thermal Storage and Battery Storage to Increase Local Self-Consumption and Grid Compatibility of PV Systems. 2012 3rd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies, Berlin.

[6] Kneiske, Barth, Hidalgo, Braun (2012). Photovoltaik-Wärmepumpen-Hybridsysteme. VDE-Kongress 2012, Stuttgart, Germany 2012.

[7] Zhang, Tezuka, Ishihara, Mclellan (2012). Integration of PV power into future low-carbon smart electricity systems with EV and HP in Kansai Area, Japan. Renewable Energy 44 (2012), pp. 99 – 108.

[8] Kinjyo, Yona, Urasaki, Senjyu und Funabashi (2012). Autonomous Frequency and Voltage Control by Decentralized Controllable Loads with Smart Grid. Journal of International Council on Electrical Engineering 2.4 (2012), pp. 415-422.

[9] Mufaris, Baba (2013). Scheduled Operation of Heat Pump Water Heater for Voltage Control in Distribution System with Large Penetration of PV Systems. IEEE Green Technologies Conference, Denver/USA.

[10] Wang, Parkinson, Miao, Jia, Crawford und Djilali (2012). Online voltage security assessment considering comfort-constrained demand response control of distributed heat pump systems. Applied Energy 96 (2012), pp. 104-114.

[11] Baetens, de Conink, van Roy, Verbruggen, Driesen, Helsen, Saelens (2012). Assessing electrical bottlenecks at feeder level for residential net zero-energy buildings by integrated system simulation. Applied Energy 96 (2012). pp. 74 – 83.

[12] Brunner, Schäfer, Rudion, Tenbohlen (2014). Auswirkungen unterschiedlicher Jahreszeiten auf den Beitrag von Wärmepumpen zur Spannungshaltung, VDE-Kongress, Frankfurt, Germany 2014.

[13] Brunner, Braun, Tenbohlen (2013). Heat pumps as important contributors to local demand-side management, IEEE PES PowerTech 2013, Grenoble, France 2013.

[14] Brunner, Braun, Tenbohlen (2013). Wärmepumpen als Möglichkeit zur Spannungsregelung in Niederspannungsnetzen. Internationaler ETG-Kongress, Berlin, Germany 2013.

[15] DIN EN 15450. Heizungsanlagen in Gebäuden – Planung von Heizungsanlagen mit Wärmepumpen. DIN Deutsches Institut für Normung e.V. Berlin, Germany.

[16] Jordan, Vajen (2005). DHWcalc: Program to generate domestic hot water profiles with statistical means for user defined conditions. Proceedings of the 2005 ISES Solar World Congress, Orlando (FL), USA 2005.