Droop Controlled Operation of Heat Pumps on Clustered Distribution Grids with High PV Penetration

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***Abstract*—In this work the impact of a high penetration of air to water heat pumps and PV plants on the distribution grid in residential areas is investigated. Results show that increasing PV penetration increases the hours of critical states in the distribution grid. Air to water heat pumps reduce those effects slightly when they are added to the grid. With an increasing penetration of heat pumps new problems, such as load peaks in the mornings, arise. By integrating voltage dependent droop control into the heat pumps, the negative effects on the distribution grid can be reduced. This reduction comes with a loss of HP efficiency and shows strong seasonal variability.**

For this study a set of representative grid layouts is used. Electric and thermal load profiles for each house are generated using the synPRO stochastic bottom-up model. The thermal load is covered by variable speed electric heat pumps combined with thermal storage. Resulting electric loads are used as input for a probabilistic load flow model.

***Index Terms*—Distribution grid, decentralized control, droop control, heat pump, DSM**

I. Increasing penetration of PV and HP offers new chances and challenges to the distribution grid

Reduction of carbon emission has become one of the key goals of international energy policy. Integrating PV systems into the power system is one way to generate renewable electricity. In German residential areas PV systems are mostly mounted as rooftop plants and feed into distribution grids. This can lead to problems in power quality. To overcome those problems additional line capacity can be installed. This comes at potentially high costs. DSM is an option to improve power quality without investing in additional grid capacity.

83% of the energy consumption in the German residential sector results from space heating and domestic hot water demand [4]. Heat pumps can be used to efficiently provide heat. Electric heat pumps combined with thermal storage offer flexibility in operation and are accepted as potential DSM technology [7], [15], [22]. Air source heat pumps (ASHP) show rising sales in the European market over the last years. Further variable speed heat pumps, which can vary compressor speed and thus electricity consumption are gaining market share [21]. The possibility to continuously vary heat pump power consumption offers the possibility to implement droop controls as DSM measure to improve power quality in the electric distribution grid.

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II. State of the Art

Heat pumps are used in various ways to support the grid. In [19] and [6] heat pumps are used to minimize the energy feed-in to the grid by local PV-Plants. Both publications don't take the grid state into account. In [5] heat pumps are used to avoid thermal overloads of transformers. In [20] and [7] heat pumps are used for decentralized voltage control. Both support voltage by switching the heat pump on and off. To avoid swinging they use a hysteresis based controller. In German grid codes droop controllers are proposed for voltage regulation [2] and used in practice. The efficiency of voltage dependent droop controllers has been shown in [8] and [24]. Consequently this publication focuses on evaluating the concept of droop controlled heat pumps for grid support.

III. Methodology

For the study of the impact of PV and ASHPs on residential distribution grids three main modelling tasks arise:

1) Modelling electric and thermal load of the connected households.
2) Modelling PV electricity generation and heat generation by ASHPs.
3) Modelling the residential distribution grid.
4) Linking distribution grid model to the household models and implementing a droop control scheme.

All models are integrated into a probabilistic load flow analysis as depicted in Fig. 1. Nodal positions within the distribution grid and sizes of PV units are determined via sampling methods based on stochastic data or populations on buildings, PV peak power and ASHPs. Nodal positions are calculated by simple random sampling whereas peak power of the PV units is derived via inverse transform stratified random sampling on the cumulated density function.

A. Stochastic Bottom-Up Model for Electric Load

Residential electric load profiles are generated using the synPRO stochastic bottom-up approach [14]. The use of the most dominant household electric devices is modelled based

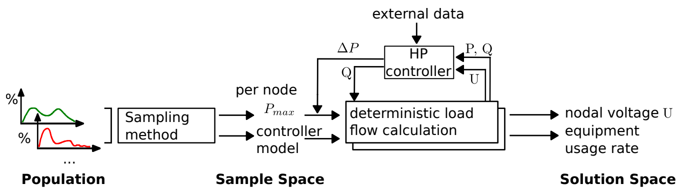

Fig. 1. Flow of probabilistic load flow analysis with heat pump controller

on behavioural data of the user. The usage model is based on probability functions of the usage frequency, typical start times and the related duration of use. Each activity is linked to measured load profile for the used electric device and an individualized electric load profile for each household is created. A description of the algorithm for generation of the activity schedule can be found in Algorithm 1. The model has been calibrated with German data [13] and validated against 400 measured profiles.

```
input  : Time Of Use Data, Device Stock Data
output: Usage Schedule for each Device
for Every Day do
    for Every Activity do
        sample Number of Starts;
        for Every Start do
            sample Start Time;
            sample Duration Given the Start Time;
            if Device is already used then
                try again;
            else
                Block Slot in Activity Schedule;
            end
        end
    end
end
```

Algorithm 1: Generation of an activity schedule used for calculation of electric load profiles.

B. Model for Thermal Load

Building thermal demand is calculated using a 5R1C building model, as described in [10]. Based on [18], reference building classes are defined depending on the buildings' energy characteristics and size. Additional variation of the thermal load profiles is implemented by randomization of buildings' orientation, temperature settings of the heating system and internal loads. Model validation against reference profiles is presented in [16].

C. Non-linear ASHP Model

The resulting heat demand of each building is covered to 100% by an ASHP combined with a thermal storage. Each system is sized such that the maximum heat pump capacity can cover the coldest 6 hours of the year. Thermal storage is sized according to manufacturers data [23] for the given HP size.

The heat pump compressor is modelled using modified AHRI-polynomials [3] for variable compressor speed obtained from compressor manufacturers. Heat exchange processes are approximated using a temperature difference at the heat exchangers which is linearly depending on transferred heat.

D. Linearised Thermal Storage Model

Thermal storage is modelled using a linear time invariant model based on energy balances of the in and out-flowing energy streams. Thermal storage is a two tank mixing storage with a control volume for DHW and for space heating.

E. HP Control

The heat pump controller operates at the heat pump at the optimum part load point as shown in Fig. 2 whenever possible. If the required heat is above this point the unit starts to increase the compressor speed and thus its heat output. If the required heat is below the unit is operated in an OnOff manner [17]. A minimum runtime of 30 minutes is implemented. The possibility to change compressor speed and thereby electricity consumption is used for droop control based on the current state of the distribution grid.

F. Flexibility and Limitations of the Thermal System

Applying a droop to the HP unit means changing the operation point at some times from what it would be when controlled to cover thermal demand in the most efficient way. This change in operation is constraint by three main limitations:

1) Change rate and number of changes is limited by system dynamics and unit wear and tear
2) Minimum and maximum available power is limited by the HP capacity
3) The timespan of possible over/under production is limited by the size of the thermal storage and the comfort requirements of the house owners

A change in compressor's electric consumption during operation is caused by a change in compressor speed. This impacts the refrigeration circuit. To enable the heat pump unit to stabilize between a change in compressor speed, a maximum change within a certain time span is set. It is assumed, that a time of 3 minutes is required for the heat pump system to stabilize after a change.

When the HP is switched on, the possibility for increasing or decreasing load is dependent on the actual point of operation as well as the minimum and the maximum thermal capacity of the unit.

Further when HP operation is changed as a reaction to grid conditions this leads to a deviation in the storage temperature, away from what it would be without that change. Whereas a higher storage temperature is unproblematic for the building owner and only limited by the heat pump's temperature limits, a lower storage temperature leads to thermal discomfort and has to be avoided. In this work it is assumed that the DHW set temperature of 55°C is also the maximum possible temperature for the HP unit. Thus the DHW part of the storage is not providing any possibility for load shifting and only the space heating part is used for a temperature increase.

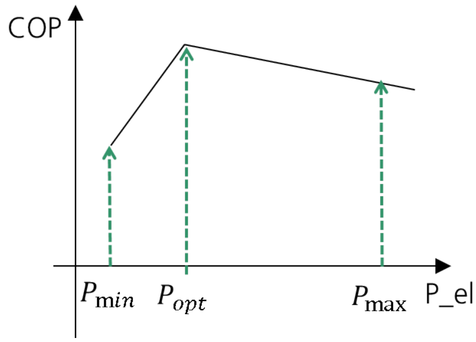

Fig. 2. Change of heat pump COP with changing heat pump capacity for fixed temperatures.

G. Coupling of thermal and electrical systems

A droop control of the heat pumps is used to improve the states of the electrical grid. Therefore the droop controls the power consumption of the heat pump. The droop characteristic depends on the voltage at its grid connection point. Consequently the electrical and the thermal system have to be regarded as one entity. The linking of the thermal household model with the distribution gird is done in two steps.

1) Thermal operation for the heat pumps is optimized to serve the thermal demand, as described within the previous sections. The resulting electric demand is feed into the distribution grid model, including the droop controllers. Storage temperature, current electrical power consumption and permissible electrical power range (min. and max.) and a the change of heat depending on the change of electric consumption at the operation point of the heat pump are provided to the distribution grid model.
2) Depending on the resulting grid state the droop control is applied and the HP pump operation is changed. Efficiency changes and changes in the output heat are calculated using the Taylor approximation values. Storage state is calculated with a simple energy balance. The control scheme ensures that operation limits of the HP and the storage are respected.

For the coupling thermal and distribution grid simulation, the time series are aggregated from secondly time steps to 10 minutely. Electrical simulations are done in a step size of 10 minutes since the corresponding specifications and laws are related to 10 minutes average mean values [1]. Due to the different time resolution of the systems and to restrictions of computation time both systems are not coupled directly. The thermal system is non-linear hence the changes are done by the droop control are not feed back to the thermal system. In the rare cases of the intervention of the droop control the change of electrical power is stored and outnumbered within the next time step. Hence there are no strong deviations from the given time series. And a direct coupling of the systems is not necessary.

H. Droop Control

ASHPs are modelled as independent and dependent on the grid states. The dependency is implemented as decentralized droop control since communication infrastructure for a centralized approach is too expensive. All heat pumps are parametrized via droop and are able to change their electrical energy demand dependent of the local grid state - the nodal voltage. In Fig. 3 the droop given to the ASHPs is shown. The droop is dependent on electrical power which is calculated within thermal simulation and on the restriction of the electrical power change that derives from temperature of the storage and the outside temperature. When there are no restrictions to electrical power the ASHP operates at its optimal power unless grid voltage leaves the secure operation limits. When the local grid voltage deviates more than 0.01 pu from the nominal voltage the consumed power of the heat pump is raised respectively reduced. The electrical power changes linearly up to 20 % until the voltage deviation reaches 0.03 pu. When there are thermal constraints the end of the droop is shifted following the original rise. Shifting the upper and the lower plateau towards the rise instead of only changing the maximal power change has the advantage that the ASHP behaves as if there where no constraints until the voltage really leaves the new rising ranges.

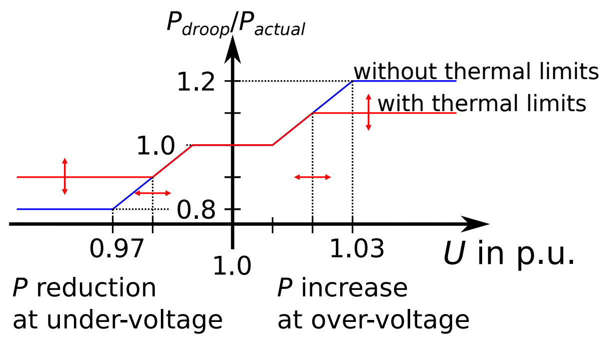

Fig. 3. P(U)-droop of the heat pump.

For the calculation of the grid states a linearised model of the ASHP is used. In order to stay as near as possible to the operating point, changes to heat pump schedule are compensated. The compensation is done storing the deviation of electrical energy input. The controller adds the deviation of input energy to the input energy of the next time step. This assures that the heating system is operated within thermal limits according to section III-F. Moreover the energy balance is not changed. To respect operating conditions of the thermal system temperature of the thermal storage is modelled.

I. Statistic PV Model

PV plant data for German low voltage grids is extracted from published EEG database [12]. Based on this data peak power distribution of PV units is calculated. The distribution is multi modal and has non-Gaussian character, which poses a challenge for sampling methods.

J. Physical Distribution Grid Model

To evaluate the results of future PV in combination with ASHP integration it is necessary to include multiple grids since distribution grids are inhomogeneous due to historically grown structures. All configurations are evaluated on benchmark clustered low voltage distribution grids as presented in [11]. All used grids are based on cable types which are characterized in Table I and use multiple costumers. This leaves nine distribution grids which are described in Table II via feeder characteristics costumer per tapped line (tapped line 1 / tapped line 2 / tapped line 3) and distance between delivery points (DP). The grids include different branching types. Its overall feeder length structures the grids. The case influences the number of DP per feeder and tapped line and thereby the number of nodes. The worse case scenario has the smallest distance between neighbouring DP in comparison to average and good case. For further information about grids and clustering method please refer to [11].

TABLE I
CABLE TYPES FOR LINE CONNECTIONS OF TAPPED LINES (A) AND FEEDER LINES (B)

Cable type	I in A	R' in $\frac{\Omega}{km}$	X' in $\frac{\Omega}{km}$	usage
NAYY 4x50mm^2	141	0.642	0.08	(A)
NAYY 4x135mm^2	275	0.206	0.08	(B)

K. Scenarios

Table III shows the investigated scenarios. Within the reference scenario only households are investigated that are located at 80, 60 and 20 % of delivery points for grids 5, 8 and 11. The penetration is chosen to fit grid characteristics and correlate with the number of delivery points. In scenario „+PV" PV-plants are added at 40, 20 and 15 % of delivery points. In "+HP" ASHPs are added to 10 % of delivery points with households. Within this scenario the effect of the heat pumps on the grid is investigated. The scenario "+droop" serves to demonstrate the effect of the P(U)-droop-control of heat pumps on the grid. It is investigated whether the number of grid critical situations is decreased by decentralized controllers.

TABLE II
SHOWCASE GRID DESCRIPTION

#	**feeder**	**case**	**DP per tapped line**	**DP distance**
4	short-range	good	03 / 02 / —	80m
5	short-range	average	06 / 04 / —	50m
6	short-range	worse	10 / 07 / —	40m
7	mid-range	good	15 / 10 / 09	40m
8	mid-range	average	20 / 14 / 11	35m
9	mid-range	worse	25 / 17 / 14	30m
10	long-range	good	30 / 15 / 12	30m
11	long-range	average	40 / 21 / 16	30m
12	long-range	worse	50 / 26 / 20	30m

TABLE III
SCENARIOS FOR THE EVALUATION OF THE GRID LOAD

Sceanrio	consumption			production
	Households	heat pumps	heat pump droop	PV
Reference	✓	✗	✗	✗
+PV	✓	✓	✗	✓
+HP	✓	✓	✗	✓
+droop	✓	✓	✓	✓

IV. EVALUATION CRITERIA

Evaluation of the scenarios is differentiated into nodal voltages and line usage rates. Nodal voltages are tested according to VDE AR-N 4105 [2] and DIN EN 50160 [1] with voltage boundaries of 3 and 4% [9] of nominal voltage, respectively. Line usage rates are necessary to characterize thermal loading of the distribution grid. They are calculated by division of the actual current by the maximal current (thermal limit). Three different cumulations of line usage rates are used:

- overall mean: characterizes the overall usage of distribution grid
- max(nodal mean): measure for worst nodal mean and in relation to the overall mean a measure for the inhomogeneity of line usage within a grid
- overall max: defines whether grid reinforcement or additional control is necessary

V. RESULTS

A probabilistic power flow analysis of a distribution grid cluster was conducted to evaluate the impact of PV and ASHP with and without droop control. A set of 4 scenarios with multiple different probabilistic load flow cases for each of the 9 distribution grids was evaluated for one year with a 10 minute time resolution in accordance with [1]. Climate data of year 2012 is used. Results are structured into evaluation of the droop controller, nodal voltages and line usage rates. Focus of results is on grids 5, 8 and 11, because these grids are presented as average cases according to [11].

A. Evaluation of Droop Controller

Droop controller results for an exemplary ASHP are presented by summarized cut electrical power $\sum P_{el}$ in Fig. 4 via carpet plot. Each vertical line represents one day. If the color of one time step is orange $\sum P_{el}$ equals zero. This indicates, that the planned schedule of the ASHP is applied. If that color changes towards red, additional power is consumed by the ASHP to decrease over-voltages with additional demand. Over-voltages are caused by the PV-units. Due to this fact, $\sum P_{el}$ above zero correlate with times of high electrical generation within the distribution grid. If color in one time step changes towards green and ultimately blue, the ASHP has decreased its demand to increase the nodal voltage. The applied algorithm targets to control $\sum P_{el}$ towards zero respecting maximal and minimal storage temperature and nominal power the ASHP as restriction. If color of a time step is not orange and does not change towards next time step these restrictions limit ASHP operation. During end of January

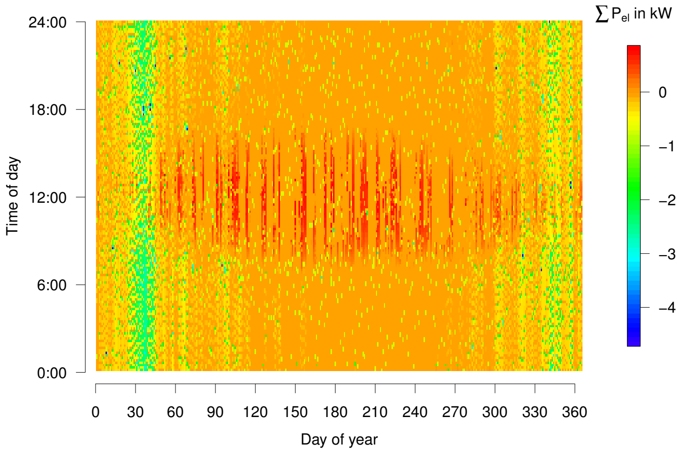

Fig. 4. Sum of cut electrical power P_{el} of exempary ASHP in distribution grid 11 and scenario "+droop".

TABLE IV
PRELIMINARY RESULTS FOR THE NUMBER OF CRITICAL STATES IN THE GRID FOR THREE YEARS (157680 TIME STEPS PER SCENARIO)

Grid Number	Scenario ID	Number of Critical System States VDE [2]	EN [1]
5	Reference	0	0
5	+PV	0	0
5	+HP	0	0
5	+droop	0	0
8	Reference	0	1231
8	+PV	0	400
8	+HP	0	482
8	+droop	0	283
11	Reference	0	24
11	+PV	40317	1
11	+HP	39853	1
11	+droop	40844	0

and beginning of February (time steps 28 to 40) ASHPs are not able to increase their electrical demand and thereby level $\sum P_{el}$ out, because due to cold weather ASHPs are running almost permanently to deliver necessary heat demand. Over the whole year probability of demand decrease of the ASHP is higher in comparison to demand increase. Yellow coloured „dots" show increased ASHP running time to decrease the electrical demand per time step and limit voltage deviation.

B. Nodal Voltages

Fig. 5 visualizes all nodal voltages per scenario and grid via box plot. Additionally voltage limits according to [2] are marked in orange color. Following paragraphs evaluate the nodal voltages per grid. Outliers are counted in Table IV. In grid 5 the reference scenario nodal voltages are below nominal voltage (1 p.u). Outliers deviate less than 0.03 p.u. from nominal voltage. With the addition of PV units („+PV") nodal voltages are increased above 1 p.u. and outliers towards over-voltages. Scenarios „+HP" and „+droop" show only slight changes in comparison to scenario „+PV". Droop control is rarely active since most of the time nodal voltage is within the dead band. Household load has major influence on the nodal voltages of grid 8. Whereas the mean of nodal voltages is almost at nominal voltage, outliers show deviations of up to 0.075 p.u. Adding PV units in scenario „+PV" decreases the number of outliers by factor 2.3 to 1.6% of the time steps in comparison to reference scenario. Adding ASHPs in scenario „+HP" increases the number of outliers by factor 1.2 in comparison to scenario „+PV" to 1.8% of the time steps. If ASHP are droop controlled the number of outliers is decreased by factor 2 in comparison to scenario „+HP". Grid 11 shows the highest count of outliers. In reference scenario 368 outliers are caused by household demand. If PV units are added in scenario „+PV" the count of outliers increases by factor 110. Adding ASHP decreases outliers by 1% points. Surprisingly, the outlier count increases if droop control is applied in scenario „+droop". If outliers are counted according to [1] trends are similar to evaluation according to [2]. In this case the number of outliers is decreased by droop control in scenario „+droop". Droop control decreases the extreme outliers efficiently. If the number of outliers is high, due to the thermal restrictions of the storage the outlier count is not decreased in all cases, because the potential of DSM is already used for extreme outliers.

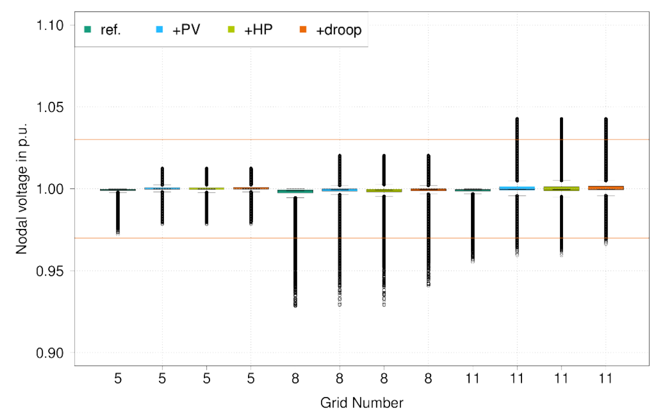

Fig. 5. Nodal voltages per scenario and grid.

C. Line Usage Rates

Line usage rate is analysed by overall maximum, maximum of nodal means and overall mean for all grids and scenarios as presented in Fig. 6. Results are discussed per grid starting with grid 5.

Overall maximum of line usage is in all scenario up 20 times higher than maximum of nodal mean an overall mean. This is a result of fluctuation of demand and generation. If PV units are added in scenario „+PV" maximal line usage rate is decreased by factor 1.6, because households use the generated energy of PV units and therefore current decreases at the beginning of the feeder. With the addition of ASHPs mean of line usage rates increases by 10%. If droop control is activated in scenario „+droop" overall maximum and mean are lowered slightly. Line usage rates in grid 8 show the same pattern.

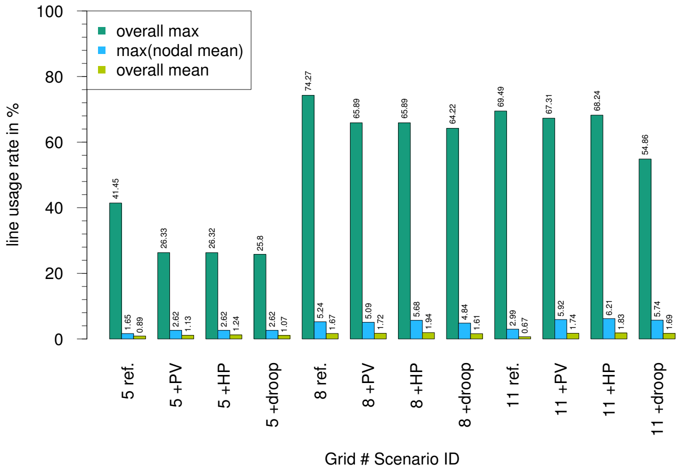

Fig. 6. Line usage rate per scenario and grid.

In grid 11 maximal line usage rate is increased if ASHP are added in scenario „+HP". In this grid ASHP have a high impact on the line usage rate. If droop control is applied the impact of the ASHP on the maximal line usage rate can be reduced significantly by 14% points. Maximum odd nodal means and overall means are also improved applying droop control.

VI. Conclusion

In this paper the effects of high PV and heat pump penetration in distribution grids are investigated using probabilistic load flow analysis. An integration of PV into the grid increases critical system states. Adding variable speed air source heat pumps to the same grid decreases the number of critical incidents due to the PV units slightly. Droop control of variable speed heat pump units is able to reduce the number of critical states. A study of the seasonal occurrence of critical grid states shows, that over-voltages due to PV feed-in mainly occur in summer, whereas in wintertime under voltage can be a challenge to the grid when adding heat pumps. In general droop controlled heat pumps can ease negative effects of a high PV and HP penetration especially during changing season. Their potential is limited by the mismatch between PV generation and heat demand. However it is shown that droop control reduces disturbing effects of a high penetration of heat pumps and gives such systems an opportunity to offer additional services to the distribution grid.

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