Sensitivity of Low-Voltage Grid Impact Indicators to Modeling Assumptions and Boundary Conditions in Residential District Energy Modeling

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Abstract

Heat pump and photo-voltaic grid impact study at low-voltage level requires detailed simulation of multiple grids and scenarios, inevitably involving assumptions and scope restrictions. This paper investigates the influence of several assumptions on grid impact indicators, namely voltage levels and load, based on a probabilistic district simulation framework developed in previous work. Grid simplification, simulation and data temporal resolution and sampling repetitions are examined, along with variation in boundary conditions, namely transformer reference voltage and capacity, and heat pump power factor. The sensitivity study shows the accuracy loss resulting from low resolution data and grid simplification, while also highlights the necessity to take into consideration uncertain parameters, such as the reference voltage and heat pump power factor.

Introduction

Heat pumps and photo-voltaic (PV) systems have emerged as efficient technologies for energy saving and CO_2 emission mitigation. However, their wide implementation in residential areas is restricted by the limited hosting capacity of current electrical distribution grids. To assess grid impact and calculate acceptable heat pump and PV penetration rates, accurate load-flow simulation of multiple grids and variability in load profiles are required. Therefore, models and methods of increased complexity and detail are necessary. However, given the intricacy of the task, assumptions and simplifications are often introduced, potentially generating conclusions of very limited validity. Sensitivity studies can provide a measure of the induced inaccuracy.

Examples of grid impact studies with sensitivity analyses include the work of Kolenc et al. (2015), who presented a network planning method to evaluate voltage conditions in grids with rising integration of distributed generation, in a probabilistic way. The Monte Carlo method was used, combined with sampling of measured load and generation profiles, to calculate the probability of voltage limit violation. The tool was used in a case study to compare the network's PV hosting capacity for different load sampling settings and transformer and PV options. Some information on the sensitivity of calculated voltage violation probabilities could be thus deduced, however only related to a specific grid without presence of heat pumps. Navarro-Espinosa and Ochoa (2016) also performed network load-flow simulations using measured load profiles and the Monte Carlo approach, to study the impact of low-carbon technologies, including heat pumps and PV, on LV distribution networks in the U.K. Sensitivity studies on several parameters and assumptions were previously carried out for the developed network assessment tool for a specific LV network with heat pumps (Navarro-Espinosa and Mancarella, 2014). Those focused mainly on network components, building and heat pump properties, rather than on modeling assumptions.

The present paper follows a more systematic approach, providing a dedicated sensitivity study of heat pump and PV grid impact indicators in residential neighborhoods. Based on a previously developed probabilistic district simulation framework (Protopapadaki and Saelens, 2017), we investigate the influence of both modeling assumptions and boundary conditions on the calculated grid impact indicators, namely voltage levels and load. The aim is to assess the accuracy of simplifications, made to reduce computation time, and to confirm the necessity of certain parameters in probabilistic grid impact analyses in general. As a result of this study, points requiring attention are highlighted and guidelines for future research in the field are provided. More specifically, different feeder modeling approaches are evaluated, considering feeders as stand-alone units, or as part of a LV distribution island. An intermediate method with *dummy* feeders is also proposed as alternative. Additionally, the influence of simulation and data resolution is investigated, as well as the required amount of building sampling repetitions for each feeder case. In terms of boundary conditions, variations in transformer capacity and reference transformer secondary voltage are considered, along with different power factors for heat pump loads.

The paper is structured as follows: In the first section, the models and modeling approach on which the analysis is based are summarized. The used grid impact indicators are then presented. In the *Sensitivity analysis* section, the general methodology is described, followed by dedicated subsections for each tested assumption. The *Conclusion* section summarizes findings of the analysis.

Table 1: Neighborhood parameters.

	Description	Values
T	Neighborhood type	rural, (urban)
Q	Construction quality	new, renovated, old
N *	Number of buildings	10, 20, 30, 40
Ca	Cable strength	weak, strong †
HP	HP penetration rate, %	0, 20, 40, 60
PV	PV penetration rate, %	0, 60
T_{kVA}	Transf. rated capacity, kVA	160, 250, 400
U_{ref}	Reference transf. voltage, pu ‡	0.95, 1, 1.05
pf	Heat pump power factor, -	1, 0.98, 0.95

* Parameter only used in original simulations and first step of sensitivity study.
† Two levels of cable cross-section area, dependent on feeder size and scenario (see Figures).
‡ pu (per-unit system): voltage as fraction of nominal voltage $U_n = 230V$.

Table 2: Main grid impact indicators.

	Description
P_f	Feeder peak real power (demand), kW
I_{max}	Peak current, A
U_{max}	Maximum 10-min voltage *, pu
U_{min}	Minimum 10-min voltage, pu

* 10-min average line-to-neutral RMS voltage, among all phases and along the entire feeder.

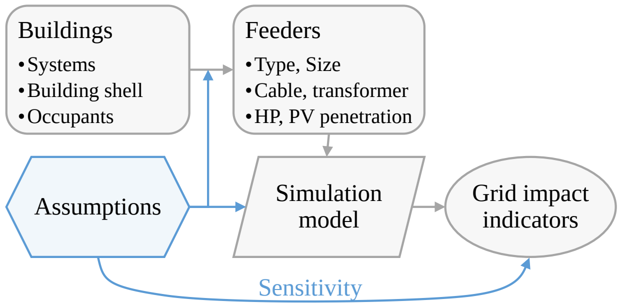


Figure 1: Overview of previously developed methodology for grid impact analysis, and introduction of new assumptions.

Model description

The sensitivity study is performed on a probabilistic simulation framework described in previous work (Protopapadaki and Saelens, 2017). This section provides a short summary of the method and models. A Monte Carlo approach is employed to simulate multiple residential feeders for a variety of pre-simulated household loads and generation. All simulations of buildings with heat pumps, the PV generation and the network are carried out in Dymola, using the Modelica `IDEAS` library, while stochastic occupant behavior is included from the `StROBe` package of `openIDEAS` (Baetens et al., 2015). This approach allows for detailed models of thermal systems, capturing their dynamic behavior in high resolution to provide input for the electrical simulations. One-year simulations are carried out for typical Belgian weather conditions.

In particular, a set of 300 buildings with heat pump was created, based on sampling of their geometric and thermal properties from predefined parameter distributions. Two-zone detailed building models are automatically generated in the Dymola environment on basis of the sampled parameters. All buildings are equipped with an individually sized air-source heat pump, that provides for both space heating via radiators and domestic hot water. The heat pump COP is dependent on operating conditions, while emission system and water storage tank are also explicitly modeled. In this paper, the same heating schedule for the hot water tank is implemented in all buildings. Each building is assigned a set of occupant profiles and is optionally equipped with a rooftop PV system. The latter consists of pre-simulated generation profiles, adjusted and scaled to the orientation and size of each particular system. Building simulations are performed independent of the feeders, to create a set of load and generation profiles. In a first assessment, unity power factor was assumed for PV, household loads and heat pumps.

The considered low-voltage (LV) grids consist of individual feeders in different configurations, supplying neighborhoods with varying degrees of heat pump and PV penetration, and buildings of diverse thermal requirements. The various feeder parameters and their respective values, derived for Belgian LV grids, are summarized in Table 1. For each feeder case, depending on penetration degrees, buildings with heat pumps and optional PV are sampled from the previously generated set. Furthermore, building sampling is repeated multiple times (N_{bs}), to cover uncertainty in building parameters, resulting in several thousand simulations. The need for computation time reduction justifies the use of pre-simulated load and generation profiles instead of integrated simulation for this study. The latter would additionally offer the possibility to apply control strategies on the heat pump operation based on grid congestion. Feeders are simulated as three-phase networks with unbalanced loading, using a quasi-stationary method.

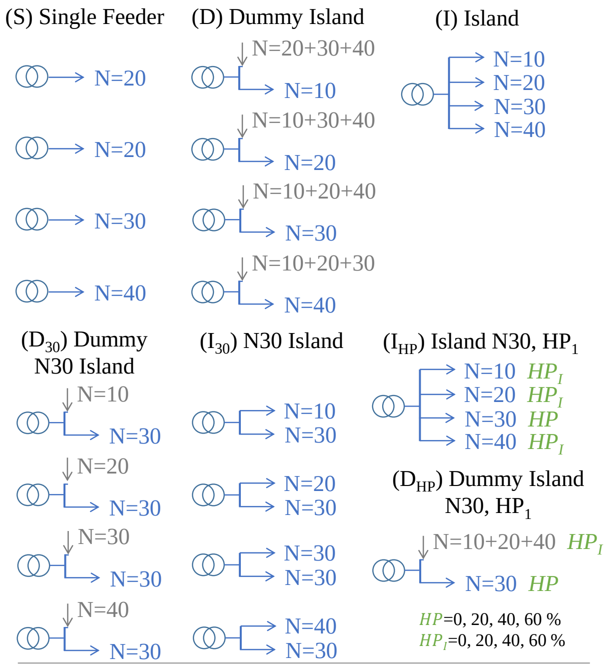
Grid impact indicators

The grid impact indicators used in the present sensitivity analysis are summarized in Table 2. These variables are selected to examine voltage violations and transformer and cable loading. Voltage level limitations are prescribed by EN 50160 (2000), which requires the 10-min average root mean square (RMS) voltage to remain within ±10% of the nominal ($U_n = 230V$) for 95% of time each week, and between +10% and -15% U_n for all time.

Cable and transformer overloading occurs when their rated capacity is exceeded. The latter is, in general, determined by the maximum permissible temperature of their components, such as the insulation material. Since this temperature depends on the equipment itself, but also on environmental and loading conditions, overloading can be acceptable under some circumstances, but no universal limitation can be determined. Therefore, in this sensitivity study, the absolute peak load and current are used to estimate grid loading for comparison among cases with different assumptions. The 10-min average values are used

Table 3: Neighborhood parameters used for each analysis.

	Modeling approach	**Time resolution**	**Sampling repetit.**	**Transformer**	**Power factor**
Q	renovated	renovated	new, renovated, old	renovated	renovated
Ca	weak, strong	weak, strong	weak, strong	weak, strong	weak, strong
HP	0, 20, 40, 60	0, 20, 40, 60	20, 40, 60	0, 20, 40, 60	0, 20, 40, 60
PV	0, 60	0, 60	60	0, 60	0, 60
T_{kVA}	160, 250, 400	160, 250, 400	250	160, 250, 400	160, 250, 400
U_{ref}	1	1	1	0.95, 1, 1.05	0.95, 1, 1.05
Heat pump pf	1	1	1	1	0.95, 0.98, 1
Total end-cases	48 × 25 (see Figure 2)	48	18	144	432
Sampling rep. N_{bs}	1	5	100	10	5
Output interval T_{out}	10	1, 5, 10, 15, 30, 60	10	10	10
Total simulations	1 200	1 440	1 800	1 440	2 160



Ca	N=10	N=20	N=30	N=40
weak	Al 4×70 mm²	Al 4×70 mm²	Al 4×120 mm²	Al 4×120 mm²
strong	Al 4×95 mm²	Al 4×95 mm²	Al 4×150 mm²	Al 4×150 mm²

Figure 2: Simulated cases for testing feeder modeling approach.

for the main comparisons; nevertheless a discussion is included in the *Simulation and data time resolution* section, where the relation with values averaged over longer duration is examined.

Sensitivity analysis

The sensitivity study employs most models from previous work. The building description and modeling remain unchanged, while different assumptions are introduced at the level of network definition and simulation. Figure 1 shows a work-flow diagram summarizing the methodology developed previously, and the new assumptions introduced at the feeder definition and simulation blocks. A major modification involves simulation of entire distribution islands, including several feeders, instead of individual feeder simulation. This results from the first sensitivity analysis step described in the subsection below. For better understanding we refer the reader to Figures 2 and 6, showing different feeder modeling approaches and a distribution island with four feeders respectively.

The sensitivity steps, each testing a specific assumption, are presented in dedicated subsections. First, the feeder modeling approach is evaluated. Then, the influence of simulation input and output resolution is discussed, followed by an analysis of required building sampling repetitions. The last two subsections investigate the importance of transformer parameters and heat pump power factor for grid impact analysis. Table 3 summarizes the subset of parameter values used in each analysis. These might differ depending on the tested assumption. For all simulations an output resolution of 10 min is used, based on the analysis in the time resolution subsection. The relative change in computed indicators and the percentage of cases violating voltage constraints are used to evaluate sensitivity to the considered assumptions.

Feeder modeling approach

A first simplification is to assume feeders as independent units, eliminating the impact of other feeders in the same distribution island (see Figure 6 for an example distribution island with four feeders). This assumption might not hold when significant loads are present in neighboring branches, creating voltage drop at the transformer. To study this effect, simulations of single feeders are compared with simulations of distribution islands with more feeders connected to the same transformer. Additionally, the use of *dummy* feeders is investigated, which is presented as intermediate solution. These *dummy* feeders are lumped loads applied directly at the transformer, without considering their position in that feeder. Here the loads are simply summed for the *dummy* feeders. In particular, the cases shown in Figure 2 are simulated with parameters summarized in Table 3. Single feeders (S) are simulated in four variants, with increasing number of customers N. For each feeder case, an equivalent island (I) and an island with *dummy* feeders (D) are simulated. Additional cases are included with smaller islands or different heat pump penetration rates for the rest of the island

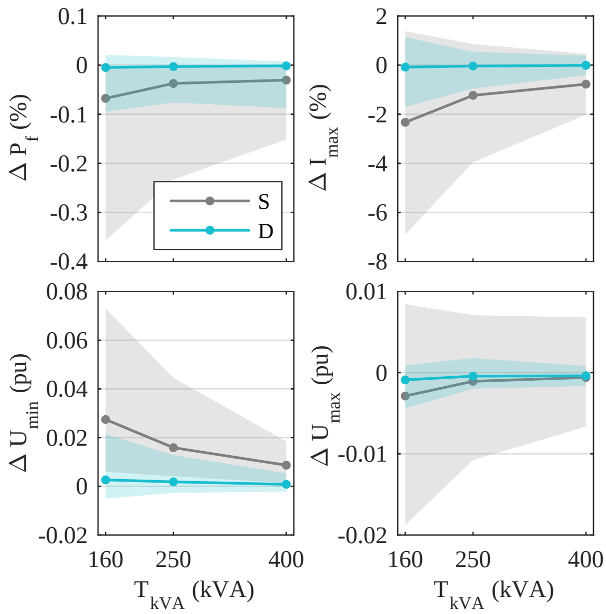


Figure 3: Differences in indicators (Table 2) for single (S) and dummy feeder (D) approaches, compared to island (I) simulations, per transformer rated capacity T_{kVA}. [1]

HP_I. Since modeling accuracy is investigated here, with main difference the feeder connection, addition of small variation from building sampling is not considered relevant. Therefore only one sampling repetition for renovated neighborhoods is used for comparison.

Figure 3 shows the percent or per unit (pu) differences of the main indicators at feeder level, for single feeder (S) and dummy island (D) simulations, compared to the full island (I) simulations, for different transformer capacities T_{kVA}. For all indicators, the error increases for smaller transformers, because neighboring feeders create larger voltage drop, influencing more the results of single feeders. As expected, individual feeders' peak load is not significantly affected; deviations are negligible, below 0.5%. Regarding U_{max}, only small over- or underestimation occurs for 0% and 60% PV respectively, as a result of neglecting generation and heat pump loads in other feeders. Over-voltage problems were insignificant for all simulations. Table 4 shows the percentage of voltage violations in different groups of simulations, for most of which no cases violated the upper voltage limit of 1.1 pu. More cases have problems close to the lower voltage limit, however, which single feeder simulations tend to underestimate. For the small transformer, single feeder simulations underestimate maximum current up to 6%, and minimum voltage up to 0.07 pu, for grids with high HP.

The found deviations are significant, but should also be considered as almost the worst-case scenario for the following two reasons: First, the simulated island contains 100 buildings in total, that is close to the 90$^{\text{th}}$ percentile of Flemish rural grids, according to Baetens (2015). In smaller islands, the deviation between model-

[1] In all graphs, lines denote the median and shaded areas contain 90% of data points, from percentile p_5 to p_{95}.

Table 4: Percentage of voltage violations per case (U_{min} <0.85 pu / U_{max} >1.1 pu).

Feeder modeling approach	S 0 / 0		D 1 / 0		I 2 / 0	
	$S_{N=30}$ 0 / 0		D_{HP} 0 / 0		I_{HP} 1 / 0	
	$S_{N=30}$ 0 / 0		D_{30} 0 / 0		I_{30} 0 / 0	
T_{out}	**1** 2 / 0	**5** 2 / 0	**10** 2 / 0	**15** 1 / 0	**30** 1 / 0	**60** 0 / 0
T_{kVA}	**160** 4 / 0		**250** 1 / 0		**400** 0 / 0	
U_{ref}	**0.95U_n** 20 / 0		U_n 2 / 0		**1.05U_n** 0 / 3	
pf	**0.95** 14 / 1		**0.98** 11 / 1		**1.00** 7 / 1	

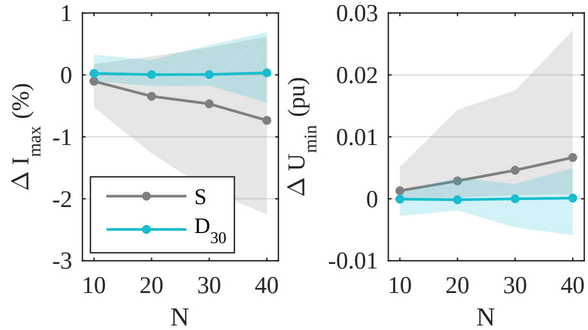


Figure 4: Differences in indicators for single (S) and dummy feeder (D_{30}) approaches, compared to island simulation (I_{30}), per number of buildings in the rest of the island N. [1]

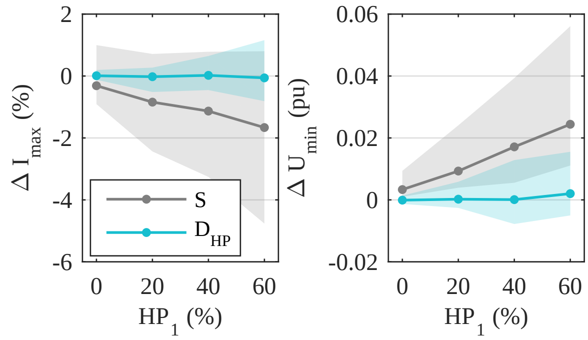


Figure 5: Differences in indicators for single (S) and dummy feeder (D_{HP}) approaches, compared to island simulation (I_{HP}), per heat pump penetration rate of the rest of the island HP_I. [1]

Table 5: Median (p_{50}), p_5 and p_{95} percentiles of CPU-time (in min) for annual simulations with modeling approaches defined in Figure 2.

	I	I_{HP}	I_{30}	D	D_{HP}	D_{30}	S
p_{95}	81	68	17	11	8.2	3.8	3.5
p_{50}	34	36	6.7	3.5	4.0	2.2	1.1
p_5	25	24	2.7	1.1	2.8	2.0	0.3

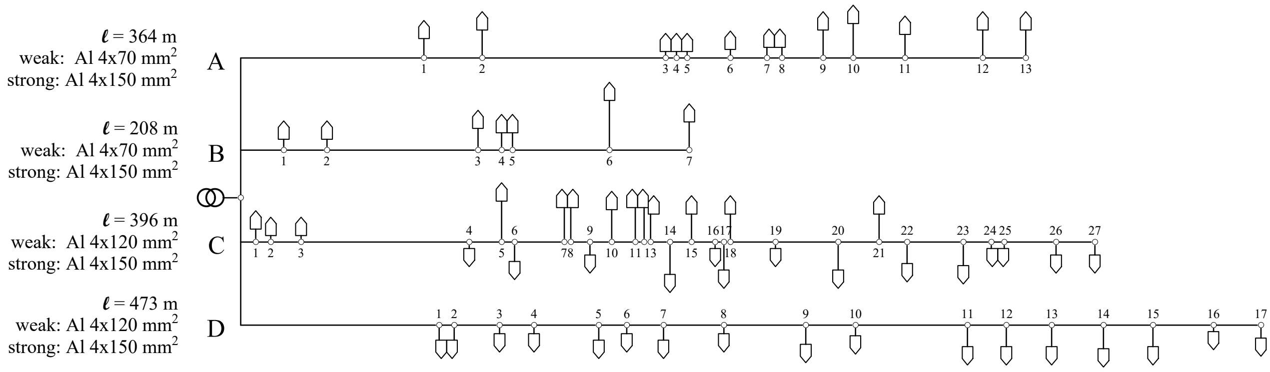


Figure 6: Rural distribution island used for sensitivity study. The layout represents a typical Belgian rural distribution island according to Baetens (2015).

ing approaches will be reduced, as a result of less stress on the transformer, as shown in Figure 4. This figure demonstrates that differences for a feeder of 30 buildings decrease as the neighboring feeder's size also decreases. Second, all feeders were assumed to have the same HP and PV penetration rates, rapidly multiplying the additional load. Figure 5 shows the deviations for a feeder with 30 buildings of the same island, when different heat pump penetration rate is applied to the rest of the island HP_I. For cases with no heat pumps in the other feeders ($HP_I = 0\%$), the assumption of feeder independence would not produce significant inaccuracies.

For all simulated cases the *dummy* feeder approach yielded results very close to the island simulations, most often below 1% and 0.02 pu. Considering also the potential savings in computation time compared to island simulation (Table 5), this solution offers important benefits in impact studies based on Monte Carlo simulations. Compared to the single feeder approach, however, both island and dummy feeder simulations create uncertainty in many more parameters defining the distribution island, thus requiring simulation of many additional cases.

In the following analysis, the island simulation approach is followed, to provide the most accurate results for evaluation of the other assumptions. A *typical* rural island in Belgian grids, as defined by Baetens (2015), serves as example. It consists of four radial feeders (A to D) with the configuration shown in Figure 6. This figure also provides information about cable types in each feeder. *Weak* versions represent a conservative estimate of existing cables in Belgian grids, while the *strong* versions represent grids with new cables, all of higher carrying capacity.

Simulation and data time resolution

In grid impact studies, network simulation resolution depends on the quantities of interest and the input data resolution, while trying to balance accuracy and computation time constraints. Regarding the first, for steady-state voltage and current evaluation under normal operating conditions, such as in this paper, time intervals of few minutes are necessary. According to EN 50160 (2000), voltage levels are examined at 10-min averages. For cable and transformer thermal loading, averaging periods of vary-

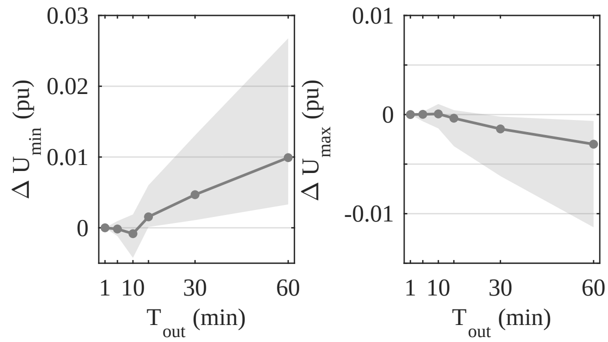


Figure 7: Differences in 10-min averaged maximum and minimum voltage per output interval T_{out}, with respect to 1-min resolution. [1]

ing length are used in literature, with up to hourly means (Navarro-Espinosa and Ochoa, 2016).

Temporal resolution of boundary conditions defines, to a great extent, the accuracy of network simulations. As high resolution data are hard to find, for instance, smart meter data are often stored at intervals of 15 min or longer (McKenna et al., 2012), sensitivity analysis of grid metrics to input resolution is of great importance. Baetens et al. (2011) have previously examined the influence of boundary condition resolution on power and voltage profiles of a specific net zero energy residential neighborhood. Due to simultaneity of loads in the grid, heat pump demand and irradiance data resolution were found to significantly impact the resulting profiles.

In the present paper, grid impact is evaluated for a variety of cases based on few indicators, rather than entire time series. This section, therefore, examines the influence of simulation output resolution (T_{out}) on those indicators. T_{out} of 1, 5, 10, 15, 30 and 60 min are evaluated. Additionally, different averaging periods dt for the maximum current I_{max} and peak load P_f are discussed. For voltage, only the 10-min average is of interest, as evaluated by EN 50160 (2000), while for I_{max} and P_f, dt of 15, 30 and 60 min are examined. For this analysis, the rural distribution island is simulated for the cases indicated in Table 3. As input profiles for household loads, heat pump load and PV generation, the high resolution profiles were

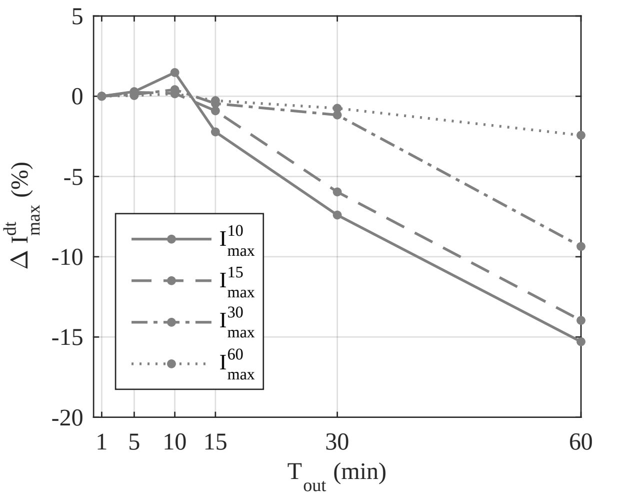


Figure 8: Median differences in maximum current averaged over periods dt, with respect to 1-min resolution, per output interval T_{out}.

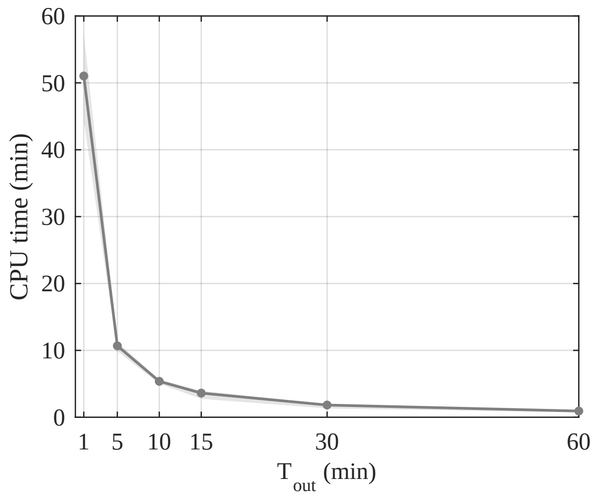


Figure 9: CPU-time for annual island simulations with different output interval. [1]

averaged to match the simulation output intervals of each case.

In Figure 7 the differences in 10-min averaged extreme voltage is shown for all T_{out}, with respect to values obtained from T_{out}=1 min. For $T_{out} < 10$ min, the indicators are extracted from 10-min moving averages, while for $T_{out} \geq 10$ min, the maximum or minimum of that profile is taken, since simple interpolation, constant or linear, would yield the same result. According to Figure 7, the minimum and maximum voltage is for T_{out} above 10 min always overestimated and underestimated respectively, reaching important deviations for hourly simulations. Table 4 also shows the percentage of cases violating the lower limit dropping with increasing T_{out}, which can be attributed to the upper 5% of highest deviations not shown in Figure 7, reaching up to 0.07 pu. On the other hand, for 10-min data, the opposite trend appears: slightly overestimating the extremes. This is because values at the end of each 10-min interval are taken as average. Nevertheless, the deviation for 10-min data remains small regarding the voltage.

Contrary to the limited voltage differences, Figure 8 reveals extremely large deviations for the maximum current I^{dt}_{max}, shown here averaged over different periods dt. Over the entire range of simulations, much higher percentage deviations were observed as well, not shown in this graph. These were, however, mainly linked to the smaller feeders, where I_{max} is far from the cable carrying capacity. As expected, the deviations increase with the simulation interval T_{out}, and decrease for longer averaging period dt. Similar results were obtained for the peak load. Since one may be interested in I^{dt}_{max} and P^{dt}_{f} averaged over periods dt longer than 10 min, we additionally state that results presented in other subsections are valid for all dt, with only small differences. Results are only plotted for the heat pump power factor analysis, where the medians of 60-min averages are also shown, only slightly differing from the 10-min average. For all other analyses, smaller deviations were found, and were, therefore, not plotted to preserve graph readability. This is also supported by the fact that correlation coefficients between I^{10}_{max} and other I^{dt}_{max} are always higher than 0.98.

Based on the results for voltage and current, simulation resolution of at least 10 min and corresponding input data are necessary for such grid impact analyses. For a probabilistic assessment with numerous simulations, however, time constraints may apply, rendering 1-min simulations impractical. The CPU-time required for annual simulation of the rural distribution island for the different output intervals is given for reference in Figure 9. Simulations were carried out on a desktop PC with an Intel Xeon E5-1620v2 processor (3.7 GHz) and 16 GB RAM. Additional benefit of lower resolution simulations is the accordingly smaller output file size, which can be an issue in Monte Carlo approaches with thousands of simulations.

Building sampling repetitions

As mentioned in the *Model description* section, several building sampling repetitions are performed in each feeder end-case, in order to obtain results with an uncertainty band reflecting the variability in building characteristics. The aim is to sample buildings enough times to obtain a distribution of results centered around the true population mean. Therefore, in this section we assess the variability of grid impact indicators for different amounts of sampling repetitions (N_{bs}) per network end-case.

Figure 10 shows the percent deviation of the neighborhood peak and total annual demand compared to the *true* mean of 10 000 repetitions. The depicted range includes a point per N_{bs} and per end-case (36 end-cases: four feeders, three HP levels and three construction qualities Q). For each end-case, the peak and total loads are calculated based on input profiles (no grid simulations) for 10 000 sampling repetitions. N_{bs} are taken randomly without replacement from the 10 000 available, and the deviation from the $true$ mean μ_{10000} is calculated. For each N_{bs}, the average of 100 iterations is taken and plotted. In short,

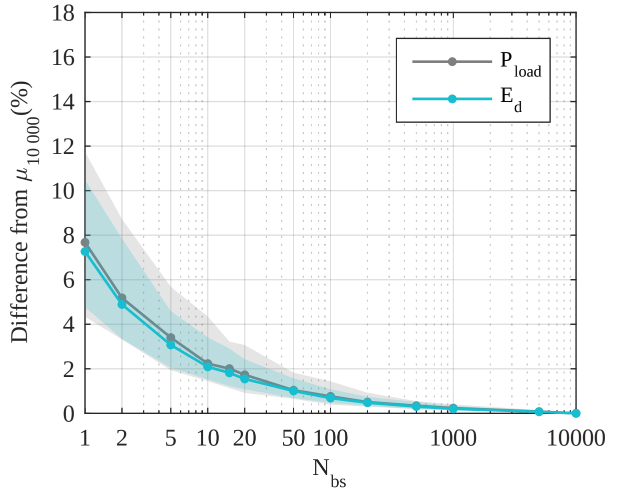


Figure 10: 100-iteration average percent deviation from the true mean μ_{10000} of aggregated peak demand P_{load} and total annual demand E_d, per number of sampling repetitions N_{bs}. Studied cases: rural feeders A to D, HP = 20, 40 and 60%, all building construction qualities. X-axis in logarithmic scale. [1]

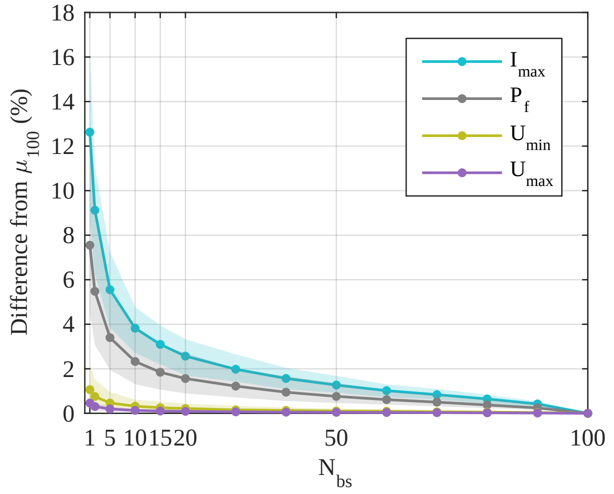


Figure 11: 100-iteration average percent deviation of indicators from the true mean μ_{100}, per number of sampling repetitions N_{bs}, and for all simulated rural island end-cases (Table 3). [1]

Figure 10 presents the average expected deviation from the *true* mean for different N_{bs}. Sampling buildings only once would result in a deviation from the $true$ mean of 12% on average, for certain cases, while for others only 4%. In general, smaller feeders and low HP penetration rates have larger deviations, as only few buildings are sampled with every repetition, making it harder to approach the *true* mean. Requiring a very small error below 1%, one would have to undertake 100 repetitions per case. However, considering the multiplicative effect of this parameter in such studies, 10 repetitions could be considered sufficient, with less than 5% error.

The impact on simulated indicators is examined using the previous approach with island simulation results. In this case, the comparison is done with the mean of 100 repetitions μ_{100}, performed for the cases listed in Table 3. For this analysis, neighborhoods without heat pumps and PV are left out, as they offer no information. Results for the four main indicators are given in Figure 11. Similar outcome is observed for P_f as found in Figure 10 for P_{load}. The maximum current I_{max} follows the same trend, with even higher deviations, especially for feeders with low demand. On the contrary, voltages have much smaller differences, always below 2% (also below 0.02 pu). Again, the same conclusions can be made: for $N_{bs} > 10$, reasonable deviations from the *true* mean of less than 5% can be achieved, while for better accuracy about 70 repetitions would be required. Of course, these results are specific to the used approach and boundary conditions, and should not be generalized without investigation.

Transformer capacity and reference voltage

In the *Feeder modeling approach* section, it was shown that the difference between modeling approaches increased as the transformer capacity decreased, due to higher voltage drop at the transformer's secondary side. The impact of transformer capacity is further investigated here. The distribution island is simulated for all cases given in Table 3, maintaining the same sets of buildings and other parameters, but with different transformers. Since current grids were not sized to accommodate significant amounts of distributed generation and heat pumps, it is valuable to examine different possible transformer capacities for the same grid for future scenarios.

Additionally, in this section we examine the assumption on reference voltage level at the transformer secondary side. In the previous simulations it has been assumed fixed at the nominal value $U_n = 230V$. However, in reality voltage variations at the primary side can cause the supply voltage to change. Furthermore, transformers may be equipped with tap changers and purposely set to provide different voltage, for instance to adjust for distributed generation (Kabiri et al., 2014). To take these variations into account, two additional reference voltage levels are considered, at 95% and 105% of the nominal, or 0.95 and 1.05 pu. Table 3 summarizes all simulated cases.

In Figure 12 the impact of transformer capacity is shown as differences in I_{max} and U_{min} compared to the reference transformer of 160 kVA. P_f and U_{max} are not displayed, since they had differences only up to 0.5% and 0.01 pu respectively. The former depends predominantly on the demand characteristics, and is therefore not influenced by the transformer. U_{max} is only slightly affected, since it is generally observed where power is injected, under reverse flow conditions. More important deviations, however, can be observed for I_{max} and U_{min}, up to 5% and 0.05 pu respectively, between the small and large transformer. Table 4 reveals the percentage of feeders with violation of the lower voltage limit increases from 0% to 4%, switching from a 400 kVA transformer to a 160 kVA one, for the same loads. Therefore this is a parameter that needs to be taken into account, not only for

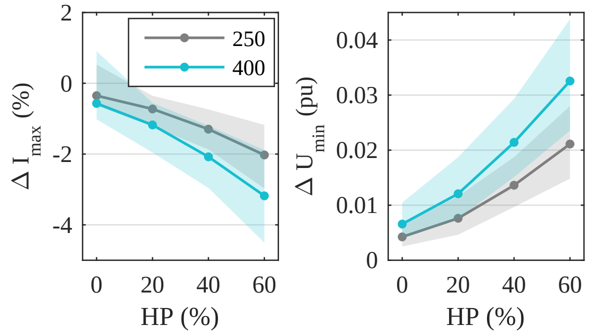


Figure 12: Differences in indicators for increasing transformer capacity T_{kVA} compared to 160 kVA transformer, per HP penetration rate.[1]

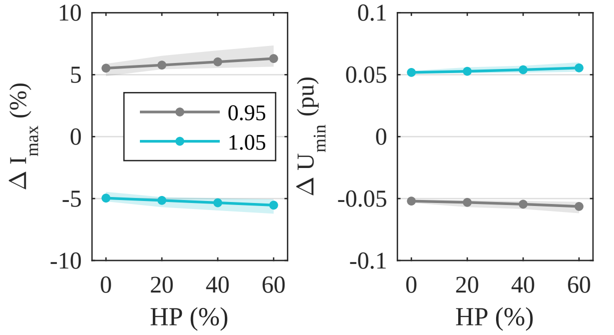


Figure 13: Differences in indicators for higher and lower transformer reference voltage U_{ref} compared to nominal 1 pu, per HP penetration rate. [1]

transformer loading calculation, but also for accurate estimation of voltages and cable thermal loading.

The relevant deviations for different reference voltage are plotted in Figure 13. Again the peak load is not influenced, while U_{max} has similar behavior as U_{min}. Both voltages follow the shift in reference voltage closely, also leading the current to change in the opposite way. 0.05 pu decrease of U_{ref} causes increase in lower voltage violations from 0% to 20% in the simulated cases, as presented in Table 4. An equivalent increase created over-voltage problems in 3% of cases instead. Navarro-Espinosa and Mancarella (2014) also found significant reduction in low voltage problems when increasing the reference voltage. Considering the high sensitivity of results to this assumption, it is advised for impact studies to include investigation of expected transformer voltage deviations due to voltage control actions, or variations at the primary side.

Heat pump power factor

In all previous simulations, unity power factor (pf) was assumed for all loads. However, heat pump components, such as the compressor, may consume reactive power, lowering the heat pump pf. This last sensitivity step investigates scenarios with more conservative pf for heat pump loads, namely 0.98 and 0.95 inductive pf, for the cases shown in Figure 3. To our knowledge, hardly any data is available regarding heat pump reactive power consumption. It is here assumed that below 0.95 heat pump

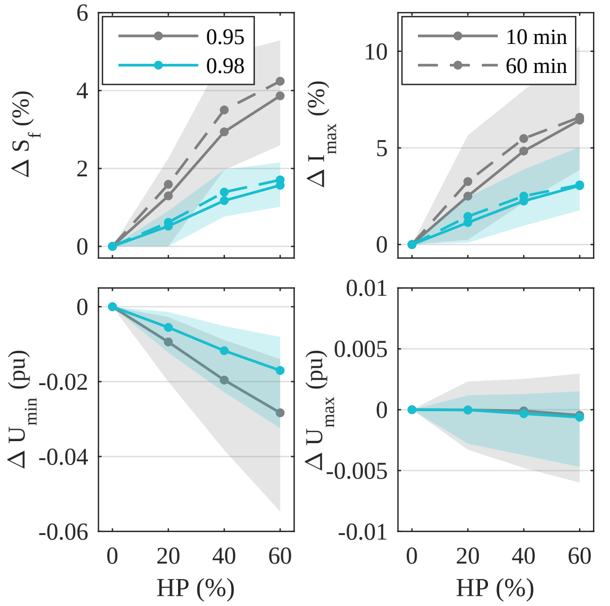


Figure 14: Differences in indicators for lower heat pump power factor pf compared to $pf = 1$, per HP penetration rate. Top-left: feeder apparent power S_f instead of real power P_f. The median for I_{max} and S_f averaged over 60 min is additionally plotted in dashed lines. [1]

manufacturers are likely to install power factor correction equipment to comply with grid operator requirements.

In Figure 14 the differences in indicators are shown for the new power factors. Peak apparent power S_f is shown instead of real power P_f, since the latter is practically not influenced by the change in pf. As $S = P/pf$ and P remains the same, S increases with a factor $1/pf$ for heat pump loads. However, the percentage difference varies per HP penetration rate because not all buildings have heat pumps, and also due to the presence of other household loads and PV generation. The apparent power averaged for 60 min instead of 10 min demonstrates the same behavior, with slightly higher deviations. The respective median differences for averaging periods of 15 and 30 min are contained between the two lines of 10 and 60 min, and are therefore not plotted.

Similar trends are reflected on maximum current and minimum voltage, as they strongly depend on the heat pump loads. The resulting differences in V_{min} are important in higher HP rates, up to 0.06 pu, leading to 4 and 7 percentage point increase in voltage violations with pf 0.98 and 0.95 respectively, compared to unity (Table 4). On the contrary, maximum voltage is not significantly affected since it occurs at low demand periods, and is more dependent on the PV generation.

This sensitivity step showed reactive power consumption may influence the grid indicators significantly, and should therefore be consider in grid impact studies. Similar findings were made also by Navarro-Espinosa and Mancarella (2014). In lack of information on reactive power consumption of particular loads, a probabilistic assessment can provide the possible expected range of the impact.

Conclusion

This paper presented a sensitivity study on modeling assumptions and boundary conditions for grid impact analysis, based on a probabilistic methodology combining thermal and electrical simulation models developed in previous work. The accuracy of modeling simplifications and the influence of certain parameters were assessed with regard to grid impact indicators evaluating voltage levels and loading.

First, it was shown that simulation of feeders individually, rather than within a distribution island, generates errors of increasing importance in cases with many heat pumps and weaker network. To cope with the dramatic increase in computation requirements for island simulations, an intermediate solution with use of *dummy* feeders is proposed, which gives improved accuracy compared to single feeder simulations. Furthermore, the analysis indicated that simulation time resolution below 10-min leads to inaccurate results, in particular regarding peak loads. To allow for simulation with smaller step, high resolution input data is required regarding demand and production profiles, provided either by more comprehensive measurements, or by detailed simulation. For probabilistic assessment of grid impact it is also necessary to account for variation in buildings and their variable demand. Based on a set of buildings representing this variation, it was shown that several building sampling repetitions are necessary in order to obtain mean indicators close to their average expected value.

Additionally, transformer capacity proved to have non negligible impact on the indicators and should, therefore, be considered as parameter in general impact studies, not focusing on existing known grids. The influence of uncertain parameters, such as the transformer secondary reference voltage and heat pump reactive power consumption, were further investigated. Both were found to significantly influence the indicators. For example, at extreme cases with reference voltage at the transformer 5% lower than the nominal, the percentage of voltage violations increases from 2% to 20%. Since detailed information on these boundary conditions is difficultly obtained, grid impact studies should include them as factors inducing uncertainty.

Even though quantitative results may be tied, to some extent, to specific simulation tools and used cases, this paper provides instructive analyses and useful guidelines for simulation experiments and studies related to the impact of heat pumps and PV on the electrical distribution grid.

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