Modeling future heat pump integration in a power radial

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Abstract

This paper considers integration of heat pumps in Danish low-voltage residential power distribution network, hereafter referred to as “radial”, providing a data-driven case study for the electrical package of the Modelica Buildings library. The loads in the distribution grid for year 2030 are estimated based on the requirement of fully sustainable energy system by the year 2050. Combined with local consumption, the total system model is validated by measuring mains transformer signal at the chosen radial. The maximum cable capacity is compared to future current flow estimations for a 2030 grid, simulated based on a specific official Danish scenario. The study shows, that there is no threat to the network cables, if only heat pumps are integrated. However, when maximum load is applied to the grid, the values of cable currents are relatively close to the limit, which may complicate integration of other technologies. The results point at recommendations for safety measures to protect electric lines during periods of rapid technological development.

Keywords: Buildings Library validation, Danish electric grid, heat pumps, photovoltaics, sustainable energy, distributed generation, electric power distribution

1 Introduction

1.1 Motivation

The Danish Energy Agency expects the heat production from heat pumps to reach 2265 GWh in 2030 equivalent to 23% of the total residential heat demand with almost linear increase over time (Energistyrelsen, 2018; Energistyrelsen, 2018a). Integration of heat pumps in the existing traditional electrical system is supposed to increase energy efficiency compared to fossil fuel-based heating sources (Bloess, Schill, et al., 2017), e.g. boilers in Denmark (Petrović and Karlsson, 2016; Nielsen, Morales et al., 2015).

However, new installations may compromise grid safety, if the increased load exceeds capacity of distribution lines designed at the previous technological stage. Similarity of heat pump control settings in different households can lead to cumulative dynamic effect of simultaneous heat consumption resulting in high peak loads in the electricity grid. Transients will, therefore, play an important role in determining cable capacity limit which should be maintained to avoid damages.

On the other hand, heat pumps can increase flexibility of the distribution grid by postponing heat production when utilizing the heat storage in buildings (Fischer and Madani, 2017). As a result, one consumer’s production can be shifted in time to match another consumer’s consumption, thereby reducing the overall peak. Real-time model predictions may play, in this case, an important role for controlling power flows in the distribution grid and mitigating simultaneity effect.

This imposes requirements on model complexity/accuracy and its computational efficiency. Simultaneous production and consumption require that the bidirectional power flows are considered. Optimized control requires that the model is either black-box or lower-order grey-box to minimize the response delay. It is however desirable to have a validated white-box model available for comparison to ensure that no overfitting occurs when estimating the reduced-order model parameters and that it can be applied outside the training data range.

1.2 State of art

Modelica Buildings library has functionality for developing computationally efficient grey-box models of multi-energy systems (Lawrence Berkeley National Laboratory, 2019). The electrical package is suitable for simulating networks with bidirectional power flows and for optimization and control combining different energy dynamics in the same model (Bonvini, Wetter, and Nouidui, 2014).

Other Modelica libraries, capable of simulating electric distribution grids are IDEAS, PowerSystems, IPSL, OpenIPSL, ModPowerSystems, ObjectStab, PNlib, Electric Power Library (Winkler, 2017; Franke and Wiesmann, 2008). However, only Buildings and IDEAS contribute to the IBPSA library, which aims to standardize district energy simulation and optimization and integrate modeling with GIS data handling.

On the other hand, commercial Modelica libraries (Electric Power Library, Wind Power Library) and non-Modelica proprietary tools (DIgSILENT PowerFactory, POWERSYS EMTP-RV, PSCADTM, Siemens

Figure 5). The current, voltage, power factor, etc. of the system were continuously monitored in the period from March 8 to March 19, 2019 by the sensor located between the grid and cable 1 (the measurement data outside of this time period is not available). Figure 9 shows the rolling average of the current measurements over the 1-hour window (orange curve), the total current simulated in Modelica (blue curve) and the root mean square error (green curve) between the two curves. Deviation of the simulated curve from the measured curve can be explained by the difference in assumed and actual ambient conditions during March 2019 resulting in a distorted PV production pattern. Additionally, the outliers seen in the figure are impossible to predict, since they depend on which appliances are connected to the cable box. In terms of the short-time load exertion on the transmission line, the peak has no real influence since the cables can handle much higher short-time current than the limit set by the providers.

Figure 9. Validation of the radial model: comparison of the electric current values calculated in Modelica (blue curve) and the measured transformer current (orange curve) over two weeks of March 2019 and the root mean square error between the measured and calculated values (green curve).

4 Results

The heat pump integration scenario simulated here is proposed by Danish Energy Agency (Energistyrelsen, 2019), which did not anticipate considerable increase in either the traditional demand or the number of PV cells. It is therefore assumed that other loads and PV production remain unchanged and only the impact of heat pump integration is considered according to the three scenarios summarized in Table 1: *Static scenario* is based on 0% forecast for the heat pump integration rate before the year 2030, which is not very probable, but will serve as a reference for other projections. *Moderate increase* scenario is based on DEA 23% projection for the electric heat pump units installed in Danish electrical system. To probe the system safety under the full heat pump penetration, the third, *Maximum increase* scenario is based on the 100% projection, corresponding to the case where heat pumps supply heat to all consumers on the radial.

Table 1. Heat pump integration scenarios.

Scenario	*Projection*
Static	0%
Moderate increase	23%
Maximum increase	100%

In Figure 10, the total currents through the supply cable 1 and the peripheral cable 8 (colored curves) calculated as $i_{tot} = \sqrt{Re(i)^2 + Im(i)^2}$ are drawn for all three scenarios. These cables were chosen because they carry the largest current for their cable sizes. As could be expected, the currents through the cable 1 are larger by absolute value than the corresponding currents through cable 8, due to the fact that the supply line is exposed to all loads. Additionally, cable 1 has 3 PV installations of 5+3 kW, 5+3 kW and 5 kW while cable 8 has none. The capacities of cable 1 and cable 8 are shown in the figure as a dotted and a solid line, respectively.

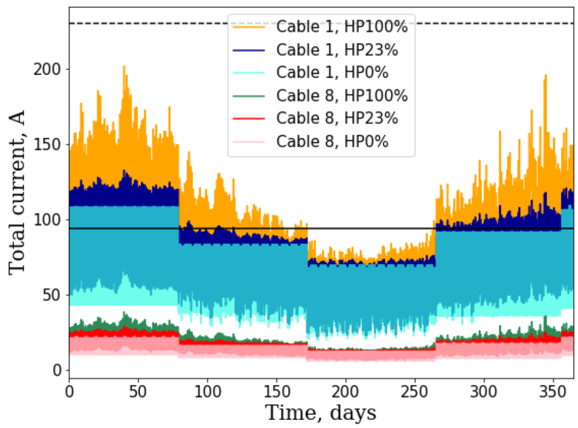

Figure 10. Heat pump penetration scenarios (year 2030). Cable capacities: cable 1 - 230 A, cable 8 - 94 A. HP0% curves are made semi-transparent.

In the wintertime corresponding to the right quarter of the figure, the current in the reference static scenario has stable amplitude, changing only during the transition periods from colder to the warmer time. During these periods, the light availability for PV generation increases, thereby reducing the current required to power the cable boxes. The sharp drops in the figure occur, because the profiles for each new season are recalculated from previous datasets, which is a normal practice to be able to forecast and plan consumption. When the heat pump load is partially included within the Moderate increase scenario, this transition effect is superposed by the variation of the amplitude within each season due to direct influence of the increased heat pump capacity on the electric system.
Further explanation can be drawn from Figure 11, which includes the same currents having the same color codes as in Figure 10, but in February of the same year.
Larger heat demand in coldest period explains the global current peak in February for Moderate and Maximum increase scenarios. However, in the latter case, the system is more sensitive to the temperature variations, and consumption is increased due to reduced heat pump COP at lower ambient temperatures and larger installed heat pump capacity. The more tangible amplitude modulation can be attributed to the effect of coincidence of the heat demand events in response to systematic reduction of the ambient temperature. This effect becomes stronger, when larger number of consumers chose the same heating strategy in the cold period. Since in present study, the simplest strategy is implemented for all active consumers, the increase of their number leads to an unequivocal effect of current fluctuations following the consumer heat consumption.

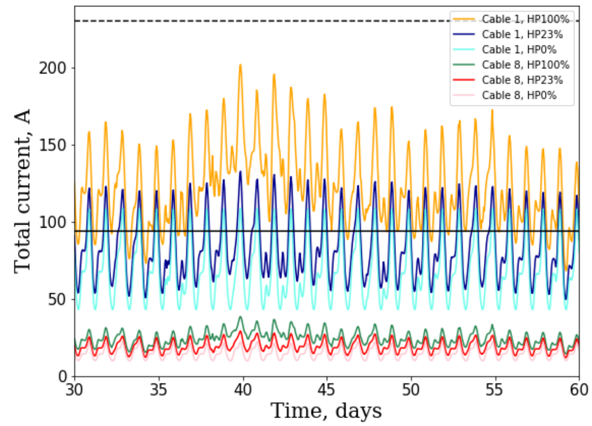

Figure 11. Total current in February 2030. The legend from Figure 10 applies.

In summer, on the other hand, the current values shown for all three scenarios in Figure 12 are close to each other, since less heating is needed, and the major part of the installed capacity is not used. The analysis of the peripherical lines (only Cable 8 is included in Figures) shows similar results with an increased current flow where heat pumps are installed and is discussed in the next section.

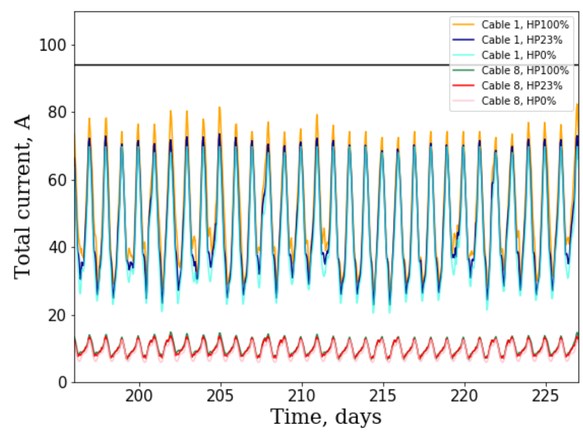

Figure 12. Total current from mid-July to mid-August 2030. Legend from figure 10 applies.

5 Discussion and outlook

Based on the obtained results, the simulated radial will perform satisfactorily for the 2030 projection offered by DEA, if only heat pumps are integrated. The supply cable 1 has the maximal mean current flow in winter equal to the half of the cable capacity in the Moderate increase scenario. The currents through peripheral distribution cable 8 and, therefore, all other peripheral cables are much less than its capacity limit.

If the radial is located in the area with 100% penetration of heat pumps (Maximum increase scenario), the current flow experiences significant seasonal fluctuations and the February peak exceeds 200 A. This and other peaks are relatively close to the capacity limit. Therefore, the integration of other technologies, such as electrical vehicles, may lead to an electrical signal exceeding the cable capacity.

The authors propose the following remedies, if the distribution currents exceed the installed capacities, which constitute the subject of future research on the topic:

1. Reduce simultaneity of consumption through load shifting and peak shaving
2. Introduce centralized model predictive control of heat pump's set points in different households to decrease the overall load on the system
3. Use flexibility of the thermal storage in buildings.

6 Conclusion

In this paper, the cable box component has been developed and validated against measurements at Danish residential radial. The component is applied to investigation of the integration of heat pumps in a typical Danish electric power distribution radial providing a data-driven case study for the electrical package of the Modelica Buildings library.

The maximum cable capacity is compared to future current flow estimations for 2030 grid simulated based on a specific Danish officials' scenario. Three simulations were performed to investigate the limit to which the distribution lines are stressed, if (1) no heat pumps are integrated in the households, (2) only 23% of the households adopted heat pumps and (3) if all households have heat pumps.

Based on the output data from Modelica and the subsequent analysis of the result, it can be concluded that there is no immediate threat to the cable capacity of the transmission lines in the radial. However, in the Maximum increase scenario, the values of cable currents are relatively close to the limit, which may complicate integration of other technologies. Therefore, to ensure the grid safety, the three solutions are proposed. The research and the model can be further modified to help the electric distribution system operators to estimate the grid load under known consumer behavior and the rapidly changing electric grid infrastructure.

Additionally, the use of Modelica as a modeling tool in the considered context offers fast and physically sound models of energy conversion systems like heat pump providing a potential benefit for dynamic simulation of sector coupling. The described model is purely electrical but can be relatively easily converted to the multi-energy system by adding relevant mechanical, hydraulic and/or thermal components. This will allow to study the influence of heat pump control and heat storage flexibility in buildings on power grid performance, which is left for future work.

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