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Application of High-Resolution Domestic Electricity Load Profiles in Network Modelling. A Case Study of Low Voltage Grid in Denmark

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Abstract
In order to capture all the particularities of electricity demand and on-site generation, e.g. the short-term spikes due use of high electricity consumption appliances such like electric kettle, and get a full picture of network performance, a high-resolution input data are needed. This paper compares the hourly network modeling with modeling when 1-minute domestic electricity demand and generation profiles are used as inputs. By means of employing 1 hour based demand and generation profiles during dynamic studies, the representation of the local power system performance might sometimes not be as accurate as needed. In the test system employed in this case the simulation indicates that no stress is created in the grid. The same investigation, but with 1-minute input data, shows that the transformer is overloaded with the values of 0.82 p.u. and the minimum voltage level is 0.922 p.u, which is below limits of common practice grid operation. The results indicate that hourly modeling network is not sufficient to capture the characteristic spikiness of the domestic load profiles and on-site generation. Hence the network overloading and high voltage deviations are not visible and the control strategies may be wrong.

Keywords - household load profiles, low-voltage network, energy modeling,

1. Introduction

The massive electrification of the Danish energy system is a fact. In all five scenarios developed by the Danish Energy Agency, which outline different models of the energy system in 2035 and 2050, an extensive electrification on the demand as well as on the supply side is foreseen [1].

This strategy is adopted to meet the 2035 and 2050 targets of 100% renewable power and heat distribution network and fossil fuel independence of energy system, respectively. As the renewable energy sources have an intrinsic variability, a stable and uninterrupted control of energy systems becomes much more complex than in case of a fossil fuel based system. In consequence of limited control over the energy supply side, the energy demand side is seen as a key to maintain stable grid operation. As the building sector accounts for 33% of the Danish final electricity use, it creates valuable potential for solving possible future network operation issues [2]. Therefore, on the national as well as on the international level there is a number of activities, e.g. iPower platform - work package 1 and 3 [3], Centre for IT-Intelligent Energy Systems in cities (CITIES) – work package 3 [4], IEA EBC Annex 67 [5], dedicated to obtain better insight into household electricity use features / patterns, and to investigate smart control strategies to unfold the existing potential.

Buildings are the very last element of the electricity distribution system. Hence depending on the grid type, their impact on the power system is most significant and visible on the level of low-voltage (LV) network (0.4 kV) and middle-voltage (MV) grids (10 kV) [6]. In common practice among utilities and network designers 1-hour input data are used when modelling LV network performance. This is the metering resolution most often adopted by the electricity supply companies as well as the resolution applied by the built environment while analyzing building energy performance. As stated in [7], the 10-minute resolution is recommended to investigate the impact of PV on the LV-networks and to get a full picture of demand distribution. In [8] instead, authors concluded that only with 1-minute resolution demand data it is possible to capture all the details and particularities of household electricity use and on-site generation. Therefore, such resolution becomes essential for obtaining a realistic representation of local distribution networks and evaluating buildings contribution to stabilize future grid operation.

According to the review by Grandjean et al. [9] only 5 models exist to provide 1-min profiles, however, these reflect cultural specifics of the country/region they are developed for and cannot be directly applied in other circumstances. The data sets and the literature on Danish electric domestic-loads are rather limited. The studies by Gram-Hanssen focus primarily on finding correlations between the electricity consumption and socio-economic factors, such as the size and year of construction of a house, the number and age of occupants, the gender, the income level, the education level [10]. The analyzed data sets are delivered by the electricity supplier and include more than 50,000 residential buildings of different topologies, but only annual values are available. Within the EU project

EURECO [11] the electricity use of individual appliances in 100 residential buildings was measured in 10-min time resolution, with the main focus on showing the discrepancy between households for each appliance and indicating the distribution of domestic electricity use. Despite having data in high resolution, the analysis was done only for the annual values. Using measurements of household electricity use from around 20 houses, Jensen et al. [12] have developed a simple method for generating 1-h load profiles for Danish households leaving in single-family houses, which later can be used as the input to dynamic simulation tool – BSim. The method is based on load profiles of a typical weekday and weekend for each of four seasons: winter, spring, summer and fall, where each hour is described as a share of the maximum hourly load during the year. The hour with maximum load is set to be on a winter weekday at17:00. No discrepancy between households is included in the method.

Based on the importance of what is previously stated, this paper aims to present a model for generating 1-minute household electricity load profiles, which give a very detailed insight into domestic electricity use and its particularities, and the application of high-resolution load profiles in LV network modeling. The analysis is conducted for a Danish LV network for two scenarios: *hourly* modeling approach, i.e. employing 1-hour based demand and generation profiles, and *minutely* modeling method, i.e. using 1-minute load and generation profiles. The obtained results are intended to outline the knowledge-gain about the household electricity use and local network performance for built environment and network planning engineers.

The paper is organized as follows. Section 2 introduces the model built for creating the 1-minute household electricity load profiles and shortly methodology used for creating 1-minute PV generation profiles. Section 3 describes the Danish LV network. Section 4 summarizes the obtained results and finally section 5 discusses the results and gives conclusion.

2. Input profiles

In this section the methodology behind the model developed to create high-resolution household demand and PV generation profiles is presented.

2.1. Household demand profiles

The 1-minute profiles of household electricity use are created using a "bottom-up" modelling approach. The model uses individual appliances and their cycle power use characteristics as basic building blocks. The structure of the model is shown in Fig. 1. On the left of the diagram, there are listed all input parameters divided between appliances, occupants and household level. To the right of the diagram, operation modules are presented, which are repeated for each household in stated order. More detailed description of methodology, the model and its validation results can be found in [13].

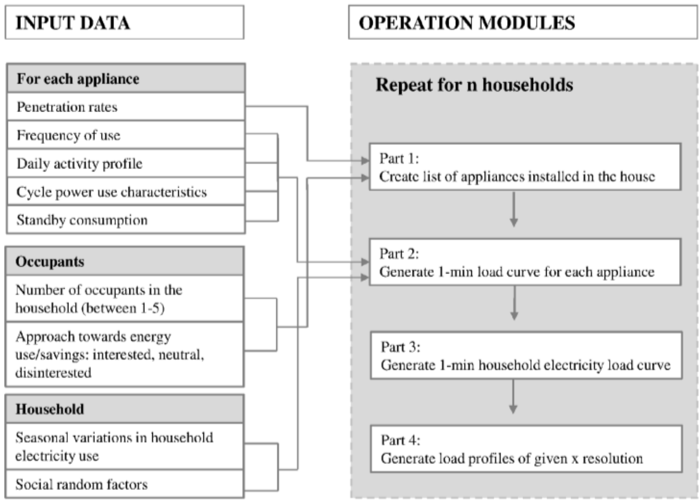

Fig.1 Electricity load model architecture

Firstly, the model populates a household with appliances. This is done on a random basis using the penetrations rates of particular appliance, with a condition that the annual household electricity demand must be within specified limits dependent on the number of occupants, calculated using (1) described in [10]. When assigning appliances to the household, the attitude of consumers towards energy use is not taken into consideration. For each selected appliance an annual electricity demand is calculated and sum of these gives the annual electricity demand of a household.

$$1988 + 773.6 \cdot \text{number of occupants [kWh/year]} \qquad (1)$$

where, 1988 kWh/year is a constant electricity use for any household and 773.6 kWh/year is the electricity use related to each occupant.

Secondly, electricity load profiles for each appliance are separately generated. For each minute a random number P between 0 and 1 is generated and a $P_{switch\text{-}on}$, which also varies between 0 and 1, is calculated using (2). When the switch-on event occurs, $P_{switch\text{-}on} > P$, at the time step t the cycle starts, and the cycle power consumption is added to the load profile of the appliance. The cycle finishes at time $t+t_{cycle}$. While the appliance is on the $P_{switch\text{-}on}$ is not calculated.

$$P_{switch\text{-}on}(a,w,h,d,n,c,\Delta t) = P_{activity}(a,h,d) \cdot f(a,d,n,c) \cdot F_{social} \cdot P_{season}(w) \cdot P_{step}(\Delta t) \tag{2}$$

where, $P_{activity}$ is an activity probability of a particular appliance (a) on a specific weekday or weekend (d) at a specific hour (h) , f is frequency of use of a particular appliance (a) dependent on number of occupants (n) and their approach towards energy saving/use (c) on a given day (d), F_{social} is a social random factor, which accounts for variations in electricity use due to short-term weather fluctuations, e.g. heavy rain or very sunny winter afternoon, which may affect the lighting and/or washing needs, as well as local and/or international events, e.g. TV shows, effecting time of use of household entertainment devices, P_{season} is a seasonal probability, which accounts for seasonal variations in household electricity use due to long-term weather fluctuations, i.e. change of seasons, P_{step} is a step scaling factor dependent on the time step (Δt).

Finally, summing up the power demands of all appliances installed within the house gives the total household specific power load profile. Fig.3(left) depicts an example of the model output for three successive weekdays for a household with three occupants with neutral approach towards energy use/savings and 25 appliances present in the house.

2.2. PV generation profiles

The high resolution generation profiles from rooftop photovoltaic are obtained for a typical PV installation located in Denmark defined by the Danish Technological Institute, see Table 1. The 1-minute values of global incident radiation I [W/m^2] on an arbitrarily oriented plane are calculated, using the transposition models outlined in [14], from 1-minute measurements of incident beam and diffuse radiation onto the horizontal plane conducted between 2008-2015 in Aalborg, Denmark. The power output – P_{PV} [W] is calculated using (3).

$$P_{PV} = A_c \cdot I \cdot \eta_{mp} \cdot \eta_a \tag{3}$$

where A_c [m^2] is the area of the PV array, η_{mp} [%] is the maximum-power-point efficiency of the solar cells and η_a [%] is the efficiency of the whole system, including cables and inverters. The η_a is assumed constant but the η_{mp} is temperature-dependent and calculated using formula given in [14].

$$\eta_{mp} = \eta_{STC} \cdot [1 + \mu \cdot T_a - T_{c,STC} + I \cdot ((T_{c,NOCT} - T_{a,NOCT}) / I_{NOCT}) \cdot (1 - \eta_{STC})] \tag{4}$$

where, η_{STC} [%] is the conversion efficiency at standard test conditions (STC), μ is the temperature coefficient of the conversion efficiency[%] , T_a

[°C] is the outdoor temperature, $T_{c,STC}$ [°C] is the cell temperature at STC, and $T_{c,NOCT}$ [°C], $T_{a,NOCT}$ [°C] and I_{NOCT} [W/m^2] are the nominal operating cell temperature (NOCT) and the related ambient temperature and incident radiation.

Table 1. Characteristics of PV installation.

<table>
<tr><td>Area
[m^2]</td><td>Slope
[deg]</td><td colspan="2">Orientation</td><td>η_{STC}
[%]</td><td>µ
[°C-1]</td></tr>
<tr><td>40</td><td>30</td><td colspan="2">South</td><td>14</td><td>-0.005</td></tr>
<tr><td>$T_{C,STC}$
[°C]</td><td>$T_{C,NOCT}$
[°C]</td><td>$T_{a,NOCT}$
[°C]</td><td>I_{NOCT}
[W/m^2]</td><td>A_{ref}
[m^2]</td><td>η_a
[%]</td></tr>
<tr><td>25</td><td>46</td><td>20</td><td>800</td><td>1</td><td>85</td></tr>
</table>

3. Test system

The selected test system is a LV network currently under operation in the northern part of Denmark. The implementation of the network model as well as all the technical assessment has been performed using the technical platform, DIgSILENT PowerFactory. The LV network is located in rural area with no access to district heating network; therefore, the buildings are heated either with the old-fashioned heating systems, i.e. oil or gas boilers, or modern solutions, i.e. heat pumps. There are 137 private consumers, which are supplied with electricity through a 315 kVA 20/0.4 kV transformer and a seven string radial network. Any relevant parameters about this piece of infrastructure such as the resistance and reactance of the grounded cables or the transformer characteristics are available in [15]. The aim of this paper is to evaluate the dynamic performance of the LV network with *hourly* and *minutely* modeling approach. Moreover, to address the future evolution of the power network towards higher share of small-scale PV installations, a static generator which represents the PV unit (PV) is added to 50% of consumers. Fig. 2 depicts loads assigned to each costumer and activated according to the selected simulation set-up.

As a simple remainder, the criteria utilized for evaluating the LV network performance during its assessment is framed according to DSO experiences. In terms of voltage, even though the European standard EN 50160 defines that the voltage at every bus of the medium voltage (MV) and LV network should be within ±10% of its nominal value, a more conservative value of a ±6%, which is applied in practice by the network designers, is considered in this case. In terms of the infrastructure loading, a maximum limit of 80% is set for both the transformer and the underground cables.

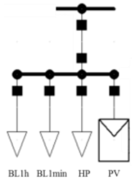

Fig. 2 Grid connection setup for a private consumer.BL,1h – hourly basic load, BL,1min – minutely basic load, HP – heat pump load, PV- photovoltaic generation

4. Results and discussion

As shown in Fig.3 the resolution of household load profiles changes the message of occupants electricity use given to utilities and network planning engineers. Although the 1-hour data reflects well the overall trend, they fail to capture the characteristic spikiness of electricity demand, which is of special interest for network operators. The load duration curves and standard deviations indicate that 1-hour data has more uniform distribution, and the high-end as well as the low-end power peaks are underestimated. Moreover, with low-resolution data, it is very difficult to recognize which appliances are used at specific time; hence, development of correct demand control strategies applicable for the future stable network operation becomes more complex.

It should be noted that the model and generated domestic load profiles were validated with the measured data on household electricity use, and good correlation was found [14].

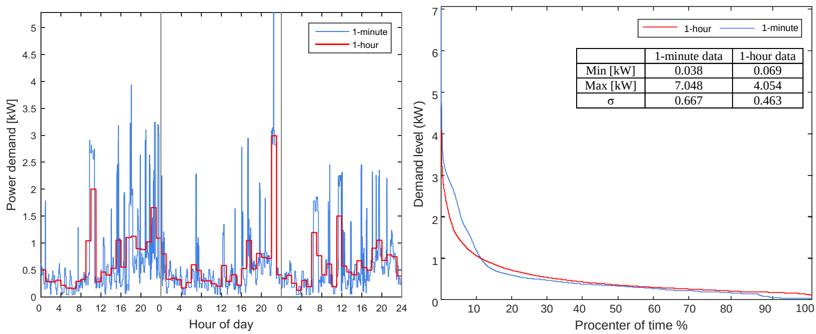

Fig. 3 Left - Household load profile in different resolutions for three weekdays in January; Right - Load duration curve of 1-minute and 1-hour data

Due to scale issue, the load or generation peaks of a single costumer are not visible at the aggregated level. Hence, the impact of increasing the resolution from 1-hour to 1-minute is evaluated on the level of local LV network. As illustrated in Fig. 4, the network performance is represented for 1-hour and 1-minute BL profiles for a winter week in February. To summarize from the top of Fig. 4, i) the loading of the transformer, which changes electricity from middle to low voltage level (L_{st} [p.u.]), ii) active power measurement at the transformer level (P_{st} [MW]), iii) the loading of the maximum loaded power line in the LV system (L_{max} [p.u.]), iiii) the maximum and minimum voltage level across the LV network (V_{max}, V_{min} [p.u.]). In case of hourly modeling, the network performs within the required limits. However, the increasing resolution of input data, gives a different message, i.e. the loading of the transformer exceeds the limit for stable operation and it reaches 0.82 p.u. during the morning Friday peak, as well the maximum loading of power lines is almost at the limit with value of 0.73 p.u. Moreover, on Tuesday evening the instantaneous power consumption of different consumers in the LV network is synchronized leading to the short-term violation of the under-voltage limit, in this case the V_{min} reaches the value of 0.922 p.u.

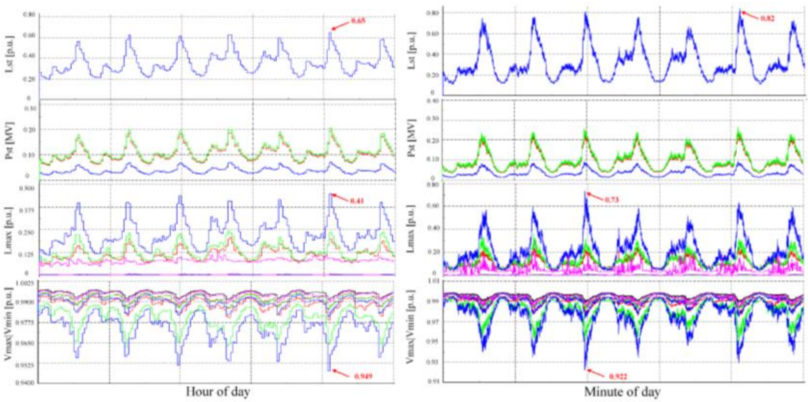

Fig. 4 LV network performance for a first week in February; left – 1-hour base load profiles and, right – 1-minute base load profiles

Since the seasonality is a factor which influences significantly the load and generation in Denmark, the winter and summer cases are compared when adding roof top photovoltaic to 50% of consumers, see Fig. 5. In the winter time, due to low sun altitude at high latitude locations, the performance of the LV network is not significantly changed. The power loading of transformer and power lines stays at the same unacceptable level. There is only small revers power flow on Friday afternoon. In the summer case instead, the maximum loading of the transformer is around 0.580 p.u. It is achieved during the evening consumption peak on Tuesday. In comparison with the winter illustration, the maximum loading point becomes lower which is reasonable since the PV generation hours are longer and thus the consumers demand less power from the grid, also in average the electricity consumption in Denmark is lower in summer than in winter [13]. Taking the aspect of significant PV generation during the summer time into consideration a LV grid energy balance gets certainly unbalanced creating as a consequence an extensive reverse power flow out of the grid.

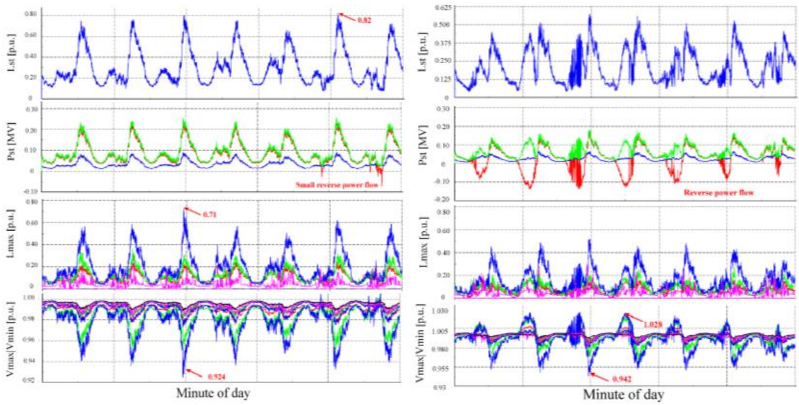

Fig. 5 LV network performance with 50% of PV; left - for a first week in February, right – for a second week in July

5. Conclusion

The electrification of the energy system, expected increase of small scale PV installations and overall aim of fossil fuel free energy system in Denmark in 2050, put new challenges for future stable network operation. As the renewable energy sources, such like wind or sun, have an intrinsic variability, the focus is shifted towards better control of energy demand. As building stock is responsible for one third of electricity consumption, thorough investigations of household demand profiles should be of great importance for network designers. The obtained results illustrate that only with high-resolution demand and generation data a full picture of network performance can be achieved, and thus correct control strategies of energy demand might be developed.

6. Acknowledgements

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