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Experimental Investigation of Power-to-Voltage Sensitivity Profiles of Residential Loads for Load Management Studies

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***Abstract*—The power-to-voltage sensitivity of a load describes how power consumption depends on changes in voltage magnitude. It is a critical system characteristic used for power system control actions such as conservation voltage reduction and voltage-led load management. Voltage sensitivity depends on the operating state of loads, which can vary over time. However, the time-varying characteristic of voltage sensitivity is often ignored in power system analysis and has been considered as a constant parameter. This paper seeks to contribute to filling this gap by experimentally analyzing the time-varying voltage sensitivity profiles of 21 common residential appliances with a sub-minute time scale resolution, conducted in a 60 m^2 apartment-like laboratory. The obtained sensitivity profiles, provided as an open-access dataset, can be used as building blocks that allow a flexible synthesis of voltage sensitivity profiles for complex aggregated residential loads. In addition to the individual load profiles, a typical daily power profile for a 2-person apartment was experimentally reproduced to study the voltage sensitivity profile of an aggregated residential load.**

***Index Terms*—Voltage sensitivity, load management, residential loads, real-lab.**

I. INTRODUCTION

TODAY'S energy system faces higher power variability due to the increased penetration of distributed Renewable Energy Sources (RESs) into the grid. The RESs gradually replace rotating masses in centralized fossil-fuel power plants, reducing system inertia and accelerating its dynamics. In the near future, to deal with the power supply of new types of electrical loads such as electric vehicles, larger energy reserve and power flexibility are needed. As a potential solution, load management provides sources of dynamic power flexibility by transforming passive loads into active resources.

Load management can be categorized into direct and indirect approaches [1]. Indirect approaches prompt customers to adjust their consumption based on the price of electricity. For example, critical-peak pricing [2] and demand bidding [3]. These require the active participation of customers and the power change is dependent on customers' decisions. Direct approaches either control customers' appliances directly or request that they consume a pre-agreed maximum amount of power. Examples include direct load control [4], [5] and interruptible/curtailable programs [6]. These schemes encounter obstacles pertaining to user comfort and customer acceptance. The voltage-led load management scheme proposed in recent years overcomes the previous challenges by modifying the load power from the utility side, without the direct involvement of each appliance [7]. As shown in Fig. 1, the voltage-led load management employs the correlation between voltage and load power (e.g. n_{pv}) and shapes the load consumption by controlling the voltage magnitude through voltage regulators such as on-load tap changers, solid-state transformers, and house-level voltage controllers [8], [9]. This power-to-voltage sensitivity n_{pv} quantifies the correlation between voltage and power, implying the available power flexibility (in blue dashed line) [10].

The existence of the power-to-voltage sensitivity has long been proved and deployed by an established technique, namely the Conservation Voltage Reduction (CVR). However, while the CVR uses the voltage sensitivity for slow and long-term energy-saving purposes (e.g. seasonal or annual), the voltage-led load management exploits it for fast power modification, which requires quantification of the voltage sensitivity in a

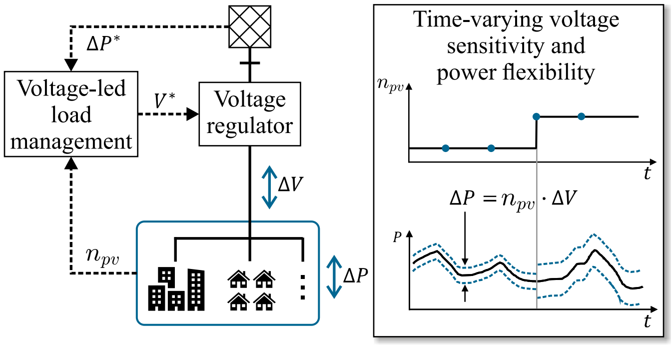

Fig. 1. Concept figure for voltage-led load management, time-varying voltage sensitivity and corresponding power flexibility.

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short time window (e.g. seconds or minutes) [7]. Although many studies have been conducted to assess the voltage sensitivity, most of them have neglected its time-varying nature [11]–[13], making them unsuitable for real-time voltage-led load management applications [8].

This paper aims to provide time-varying voltage sensitivity profiles of individual and aggregated residential loads, with a sub-minute timescale resolution. The profiles are based on experiments with real residential appliances. The main contributions of the work are as follows:

- Time-varying voltage sensitivity profiles on appliance level with sub-minute resolution. The sensitivity profiles indicate the range of an appliance's sensitivity during operation, which have been oversimplified as a constant in previous works.
- This work includes an open-access database of experimentally identified voltage sensitivity profiles for appliances [14], which can be utilized as a foundation for synthesizing time-varying voltage sensitivity profiles for complex aggregated residential loads.
- The voltage sensitivity profile of a 2-person apartment during a typical working day is provided. The result provides an estimation of the power flexibility that an apartment can offer daily by means of voltage-led load management.

The rest of the paper is structured as follows. Section II provides an overview of the state-of-the-art voltage sensitivity results and discusses their limitations for voltage-led load management applications. Section III explains and discusses methods for voltage sensitivity identification and aggregation. Section IV presents the experimental setup for sensitivity identification and the identified sensitivity profiles of household appliances. Section V provides the sensitivity profiles of an apartment and the experimental validation of the proposed sensitivity aggregation formula. Section VI discusses how the provided sensitivity data can potentially be expanded and applied to a broader range of appliances and operating scenarios. Eventually, conclusions are drawn in Section VII.

II. STATE OF THE ART: VOLTAGE SENSITIVITY

A literature review of studies on the power-voltage correlation is conducted in this section. As a prior for voltage-led load management, the power-voltage correlation is usually described with voltage sensitivity and load models, such as the exponential model and the polynomial model (ZIP model). Voltage sensitivity represents the ratio of the percentage change in power to the percentage change in voltage and is equivalent to the exponent of an exponential model [10]. It provides a simple and intuitive quantification of the correlation, making it very suitable for load management applications. Therefore, voltage sensitivity is used to describe the power-voltage correlation in this paper.

Table I presents a comprehensive overview of key studies on the power-voltage correlation. Research considering the load power sensitivity to voltage has been carried out since the 1940s to provide accurate descriptions of the load behavior for power system analysis [15]. Since then, there has been a renewed interest in studying voltage sensitivity due to the emergence of new types of loads [11]–[13], [23], [24]. However, all of these studies described the voltage sensitivity using constant values ignoring the time-varying nature of voltage sensitivity.

In recent years, a few studies have considered the time-varying characteristic of voltage sensitivity at the substation level [25]. In [18], [20], the voltage sensitivity of substations was simulated by aggregating constant voltage sensitivities for appliances following power profiles generated by the CREST Tool [26]. Their results emphasized the importance of accounting for the time-varying characteristic of voltage sensitivity in voltage-led load management applications. In [19], [22], calculation methods for the CVR factor (equivalent to voltage sensitivity in these papers) are proposed. The calculation results, based on measurements from substations, are provided with 1-hour and 15-minute time intervals. In addition, the Customer Load Active System Service (CLASS) project in the UK conducted a systematic study on 60 primary substations between June 2014 and May 2015 to measure the available power flexibility from load management [21]. The study provides voltage sensitivity with a 30-minute time resolution. Voltage sensitivity is calculated from the normal actions of tap-changers throughout a year, which are classified into 8 classes according to season, weekday, or weekend. By merging the results of a class into a single day, voltage sensitivity at different times of the day is obtained. A sensitivity matrix over 24 hours with a 30-minute resolution was developed by averaging data with 30-minute intervals, using different averaging windows such as 30 minutes, 1 hour, etc. However, the sensitivity profile is not obtained from consecutive measurements and is very likely to have empty sensitivity values in the averaging window, leading to deviation from the actual result. To reduce such problems, in this paper, voltage sensitivity is determined from artificial voltage variations and consecutive measurement data.

Although the time-varying sensitivity of the substation has been studied extensively through field tests, the results may not be applicable to other substations due to differences in load composition. This can be observed among the results of UK 60 substations [21] and results from different countries [20], [27]. On the contrary, the individual residential appliance technology does not vary greatly between substations and even between some countries, making the voltage sensitivity of appliances versatile. However, voltage sensitivity at the appliance level was never provided with time-varying. Therefore, in this paper, the voltage sensitivity of 21 typical residential appliances is studied experimentally with 15-second time intervals. Moreover, a typical daily power profile for a 2-person apartment was reproduced to estimate the power flexibility an apartment can provide over a day. It is worth noting that all the sensitivity profiles can be used as components to aggregate the sensitivity profiles of complex loads.

III. VOLTAGE SENSITIVITY AND IDENTIFICATION METHODS

This section defines the voltage sensitivity mathematically and introduces and motivates the sensitivity identification

TABLE I
POWER-VOLTAGE CORRELATION STATE OF THE ART

Ref.	Year	Main Focus	Power-Voltage Correlation Description	Individual Load	Time Resolution - Individual Load	Aggregated Load	Identification Method for Aggregated Load	Time Resolution - Aggregated Load
[15][1]	1982	Load model for power system analysis (overview results 1940-1980)	Voltage sensitivity	✓	✗	✓	field test	seasonal
[11]	1998	Load model for system analysis	Exponential & ZIP model	✓	✗	✓	aggregation	✗
[16]	2008	Load model for system analysis	Nonlinear load model [17]	✗	-	✓	field test	day-part
[18]	2013	Voltage-led load management effect assessment	ZIP model	✓	✗	✓	aggregation	1 min
[12]	2014	Load model for CVR effect assessment	ZIP model	✓	✗	✓	aggregation	✗
[19]	2014	CVR factor identification	CVR factor[2]	✗	-	✓	field test	1 h
[20]	2015	Voltage-led load management effect assessment	Exponential model	✓	✗	✓	aggregation	1 min
[21]	2015	Voltage-led load management effect assessment	Exponential model	✗	-	✓	field test	30 min
[22]	2022	CVR factor identification	CVR factor[2]	✗	-	✓	field test	15 min
This paper	2024	Voltage sensitivity for voltage-led load management applications	Voltage sensitivity	✓	15 s	✓	appliance-level test	15 s

[1]: The review paper is cited as a substitute for the original data sources, as many of them are unavailable or inaccessible.

[2]: In these papers, the CVR factor represents not the correlation between energy and voltage but power and voltage. Thus, equivalent to voltage sensitivity

method used in the paper.

A. Definition of Voltage Sensitivity

The time-varying power-to-voltage sensitivity is defined as [28]:

$$n_{pv}(t) \overset{\text{def}}{=} \left.\frac{\mathrm{d}P(t)/P_0(t)}{\mathrm{d}V(t)/V_0(t)}\right|_{V(t)=V_0(t)} \tag{1}$$

$$n_{qv}(t) \overset{\text{def}}{=} \left.\frac{\mathrm{d}Q(t)/Q_0(t)}{\mathrm{d}V(t)/V_0(t)}\right|_{V(t)=V_0(t)} \tag{2}$$

where t represents the time-varying characteristic. n_{pv} and n_{qv} are the active and reactive power-to-voltage sensitivity, respectively. V is the Root Mean Square (RMS) value of the actual operating voltage. The subscript 0 indicates the rated value. P_0 and Q_0 are the rated active and reactive power at the rated voltage V_0. Note that the rated voltage can be chosen arbitrarily and is not necessarily the nominal voltage.

The voltage sensitivity reflects the impact of changes in voltage on load power. For instance, a value of $n_{pv} = 2$ indicates that a 1 % reduction in the initial voltage V_0 leads to a 2 % decrease in active power P_0. Conversely, if a voltage reduction results in an increase in power, the voltage sensitivity will be associated with a negative sign.

B. Time-Varying Characteristic of Voltage Sensitivity

The voltage sensitivity value of loads is determined by the physical characteristics of the operating components and the control logic of their internal controllers. The sensitivity varies when these characteristics change. The time-varying characteristic of voltage sensitivity is primarily caused by two factors [29]: *i)* the state changes of individual appliances during operation; *ii)* the turning on and off of different appliances, which is related to the lifestyle of the household inhabitants. For instance, the probability of the washing machine being on varies at different times of the day. When the washing machine is on, the dominant operating component switches between a resistor for heating and a motor for rotating. The power change in a resistor is proportional to the square of the voltage change ($n_{pv} = 2$), whereas the voltage sensitivity of the motor, depending on its control and construction, is usually below 2 ($n_{pv} < 2$). Consequently, throughout the day, the voltage sensitivity of a washing machine varies over time: it is 0 when the machine is off, equals 2 in the heat-up state, and below 2 in the rotating state. The value of voltage sensitivity can change significantly over time, and therefore, the voltage sensitivities are provided as time profiles in this paper.

C. Voltage Sensitivity Identification Methods

Typically, identification methods for voltage sensitivity can be classified into measurement-based and component-based method [13], [23]. The measurement-based method considers aggregate loads as a single entity. It measures power responses to natural or artificial voltage variations and calculates the voltage sensitivity accordingly. On the other hand, the component-based method takes the load composition and the voltage sensitivity of the components as a prior. It composes the voltage sensitivity of the aggregated load using the existing knowledge of individual loads.

For individual appliances, the exact composition is very difficult to obtain, while a test environment can be easily achieved in a laboratory due to the relatively low test power. Thus, in previous studies and also here, the voltage sensitivity of appliances is determined using the measurement-based method. A decision between measurement-based and component-based methods is often required for aggregated loads, as neither the exact load composition nor a test environment is easy to obtain. The measurement-based method provides realistic estimation while the component-based method offers a versatile and cost-efficient solution.

In this paper, the voltage sensitivity of individual appliances is identified with the measurement-based method with artificial voltage perturbations, which is also known as the perturbation-based method. An apartment is studied as an example of aggregated residential load with the same perturbation-based method. The identified sensitivity profiles are provided with an aggregation formula, enabling them to serve as components for component-based methods.

D. Perturbation-Based Sensitivity Identification Method

The perturbation-based sensitivity identification method is a subset of the measurement-based method. It applies artificial voltage perturbations to the load under test, changing for a short time the voltage amplitude enabling sensitivity identification [10]. Compared to natural voltage fluctuations, the occurrence of an artificial voltage perturbation is fully controlled. This is a significant advantage for load management applications as the voltage sensitivity can be updated with the desired time resolution or at specific times. In this work, the voltage sensitivity is determined by changing the voltage magnitude and measuring the power response. A 0.8 Hz sinusoidal disturbance signal with a magnitude of 5 % of V_0 is added to the load voltage magnitude. The voltage variation lasts 5 s and is triggered every 15 s.

In Fig. 2, the RMS profile of the voltage is presented in the top subplot in blue. Note that the sinusoidal variations are changes in the voltage magnitude. The power profile is shown in the middle subplot in blue. Based on the voltage and power profiles during the sinusoidal variation, the active power-to-voltage sensitivity is calculated by (3) (explained in detail later) and presented in the bottom subplot in blue. The red parts in the voltage and power profile mark out where V_0 and P_0 are calculated before each disturbance and the red dots in the sensitivity subplot represent the voltage sensitivity average of each identification period.

Assuming that the exponential model describes the load behavior accurately, the rated point (V_0, P_0) in (1) can be any operating point (V_k, P_k) and the sensitivity value remains unchanged [10]. Hence, the active power-to-voltage sensitivity can be calculated as below:

$$n_{pv} = \left.\frac{\mathrm{d}P/P_k}{\mathrm{d}V/V_k}\right|_{V=V_k} \approx \frac{(P_k - P_{k-1})/P_k}{(V_k - V_{k-1})/V_k} \tag{3}$$

where the subscript k denotes the current calculation step, and the subscript $k-1$ denotes the previous calculation step. The same also applies to the calculation of reactive power-to-voltage sensitivity.

The voltage RMS value and the power here have a resolution of 50 ms. A voltage sensitivity is calculated every two data points for higher accuracy [30]. During the voltage variation phase, the voltage sensitivity is calculated consistently (Fig. 2 bottom plot in blue). As mentioned previously, for noise rejection, the voltage sensitivity and the corresponding rated point are updated once per voltage variation phase (15 s resolution), where their average over the variation phase is used (Fig. 2 bottom plot in red).

E. Time-Varying Sensitivity Database and Aggregation Formula

As explained above, in this paper, the voltage sensitivity of a load is a time profile with a resolution of 15 s. Therefore, the voltage sensitivity identification result of each load is provided as a table with 4 columns: time stamp (time_s), voltage sensitivity (n_{pv} or n_{qv}), rated power (P_0 or Q_0), and rated voltage (V_0). The sensitivity data is available as open-access information, serving as valuable component sensitivity details for component-based methods.

Since the perturbation-based method is used to determine the voltage sensitivity, the voltages of the tested loads are

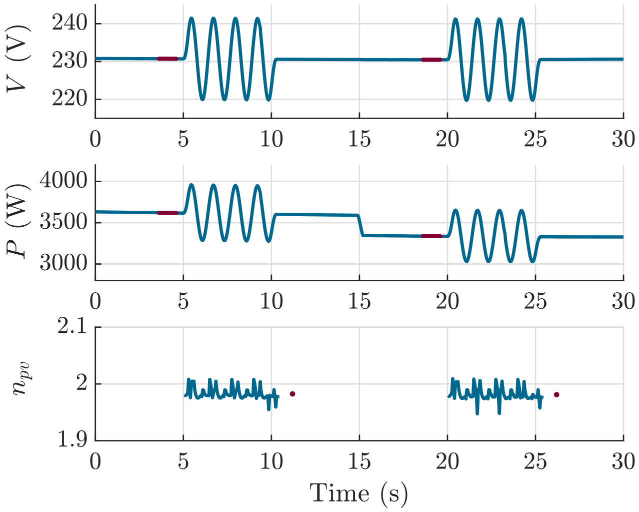

Fig. 2. Results of an oven as an example for perturbation-based sensitivity identification method: Top subplot, RMS value of voltage measurements; Middle subplot, active power measurements; Bottom subplot, voltage sensitivity calculated during voltage disturbances.

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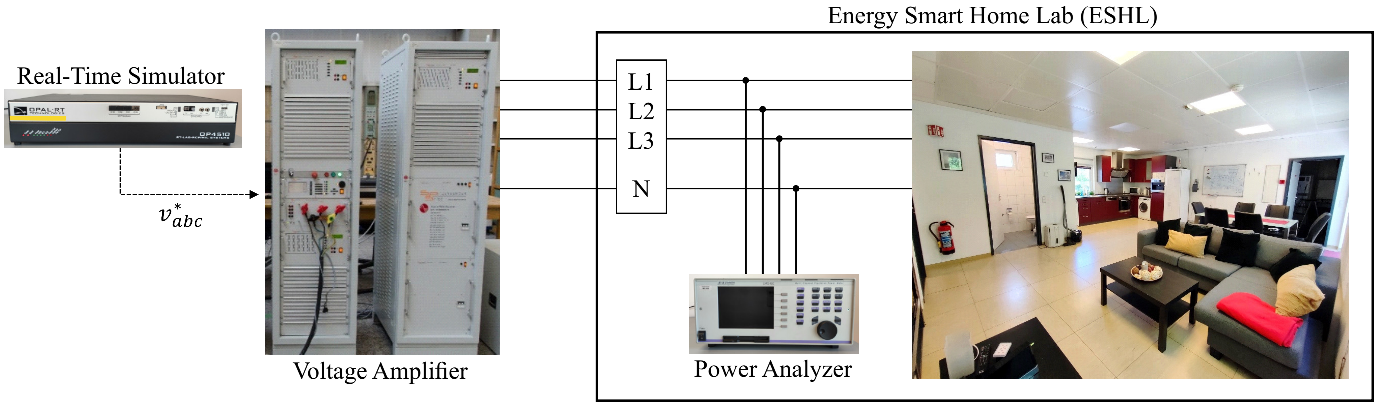

Fig. 3. Experimental setup with the Energy Smart Home Lab for voltage sensitivity identification of residential loads.

actively controlled and can be assumed identical. Thus, the following formula can be employed to construct voltage sensitivity profiles for the aggregated loads from the sensitivity of its components, such as individual appliances:

$$n_{pv,\mathrm{agg}}(t) = \frac{\sum_{i=1}^{i=n}(n_{pv,i}(t) \cdot P_{0,i}(t))}{\sum_{i=1}^{i=n} P_{0,i}(t)} \tag{4}$$

n denotes the number of components, $n_{pv,i}$ and $P_{0,i}$ are the voltage sensitivity and the rated power of the i-th component, respectively. The formula for reactive power-to-voltage sensitivity aggregation can be obtained in the same way. It is worth noticing that the rated power of a load represents the impact factor of its voltage sensitivity. The higher the rated power is, the larger the impact is.

IV. VOLTAGE SENSITIVITY PROFILES OF INDIVIDUAL LOADS

In the previous sections, the definition of power-to-voltage sensitivity and the identification methods are explained. In this section, the perturbation-based method is used to determine the voltage sensitivity profiles of residential appliances. The experimental setup with an apartment-like laboratory is explained in Section IV-A. The voltage sensitivity identification results are illustrated in Section IV-B.

A. Experimental Setup

The Energy Smart Home Lab (ESHL) is a fully functional $60\,\mathrm{m}^2$ apartment-like laboratory consisting of a living room with an open kitchen, two bedrooms, and a bathroom [31]. The ESHL enables tests with actual residential loads. To be able to generate voltage magnitude variations, the ESHL is connected to three four-quadrant voltage amplifiers (one for each phase), as shown in Fig. 3. The voltage amplifiers are controlled by an OP4510 real-time simulator by OPAL-RT. Currents, voltages, and powers are measured by an LMG450 power analyzer by ZES Zimmer. The power of the entire ESHL is measured, but each appliance in the apartment can be turned on or off individually through the control panel, allowing us to determine which load is being tested.

On identifying the voltage sensitivity, a three-phase voltage signal with periodic variations in magnitude is generated by the real-time simulator and sent to the voltage amplifiers. To guarantee that only the power of the target appliance is measured, one load is connected to each phase. As the power of the three phases can be measured separately, three tests of individual appliances can be conducted in parallel. Each appliance is tested under one realistic operating mode and the test duration is mostly decided by the load, e.g. how long the washing machine runs.

TABLE II
LIST OF LOADS UNDER TEST

Load	**Brand and Model**	**Tested Operating Mode**
Induction stove	Miele KM 5955	Maximum power level
Water kettle	Clatronic WKS 3692	Cook 1.5 L water
Oven	Miele H5681BL	Top and bottom heating, set temperature 280° C
Oil radiator	Clatronic RA 3735	Set temperature 24° C
Electric cook plate	Clatronic EKP 3582	Maximum power level
Condenser dryer	Miele T 8687 C	Gentle cycle
Hair dryer	Impuls SL-805	Maximum wind level, medium heat level
Microwave oven	Renkforce MM720Ca7-PM	Cook mode power level 4
Toaster	Severin AT 2586L	Maximum power level
Air conditioner	KOENIC KAC 9022 B WLAN	Cooling with maximum wind level, set temperature 17° C
Dishwasher	Miele G 1834 SCI	Quick wash 40° C
Halogen ceiling lights	–[a]	Lights on
Vacuum cleaner	Siemens VBBS607V00	Smooth surface cleaning mode
Cooker hood	IKEA[b]	Medium extraction level
Washing machine	Miele 3985 WPS	Cotton wash 1000 rpm
Freezer	Liebherr GN 3056-29	set temperature -20° C
Laptop charger	TOSHIBA PA3755U-1ACA	As power supply
LED light	–[a]	Light on
Fridge	Bosch KG KIRR18A	Maximum cooling level
Fan	BaseTech VE-5985BT	Maximum power level with head shaking
Monitor	Samsung BX2240	Monitor on

[a] Brand and model information not available
[b] Model information not available

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B. Voltage Sensitivity of Residential Appliances

This section investigates the voltage sensitivity of typical residential appliances over time. Each appliance is tested under a realistic operating mode listed in Table II. The identified voltage sensitivity is offered as a time profile. Several examples of the voltage sensitivity of individual appliances will be provided in the following parts of this section.

As explained in Section III-D, a variation in the voltage magnitude is triggered every 15 s to determine the voltage sensitivity, the rated power, and the rated voltage. The provided voltage sensitivity profile has then a timescale resolution of 15 s.

1) Example of a dishwasher: In Fig. 4, the rated powers and voltage sensitivity profiles of a dishwasher are presented. The rated voltage profile is almost constant around the nominal voltage and thus is not presented in the figure. The dishwasher operates in the quick wash mode containing three main operating phases: a washing phase, a rinsing phase, and a drying and draining phase. The heating element, the circulation pump, and the spray arm motor are the three main elements of a dishwasher. The heating element can be considered as a large resistor and dominates the active power-to-voltage sensitivity of the dishwasher. Meanwhile, the motors dominate the reactive power-to-voltage sensitivity. In the washing and drying phase, the heating element operates, the active power reaches 2000 W and a n_{pv} of almost 2 is observed, indicating a constant impedance load behavior. Furthermore, when the circulation pump and the spray arm motor (both uncontrolled motors) operate, the reactive power reaches 100 var and a n_{qv} around 0.5 is observed.

2) Example of an air conditioner: Air conditioning systems play an essential role as residential loads, especially in summer times. They consume relatively high power and operate for a very long time. Here an air conditioner is tested under cooling mode for 70 minutes. The sensitivity profiles are presented in Fig. 5. The tested air conditioner does not have an inverter for smart power control and the compressor is directly connected to the grid. This air conditioner operates in cycles, switching between the cooling mode (compressor on) and fan mode (compressor off) to make the room temperature follow the set temperature. As shown in Fig. 5, in cooling mode, the power consumption reaches 900 W and 100 var, with n_{pv} around 0.4 and n_{qv} around 3. In fan mode, the power consumption decreases to 50 W and 10 var. The voltage sensitivity n_{pv} reaches 1.7 while n_{qv} is considered 0 since the reactive power is below the calculation limit of 20 var. It is worth mentioning that a freezer with a directly connected compressor is also tested and shows n_{pv} around 0.4, which is very close to the air conditioner in cooling mode. And a fan shows n_{pv} around 1.9, close to the air conditioner in fan mode, due to the use of similar technologies.

3) Example of an oven: Another example is given in Fig. 6. It presents the voltage sensitivity profiles of an oven. When the oven is turned on (around 2 min) all the heating elements operate and the oven reaches 3600 W and 50 var. When the oven reaches the set temperature (around 8 min), it starts to operate in the heat-insulating mode with lower power. During the operation, although the heating mode changes and P_0

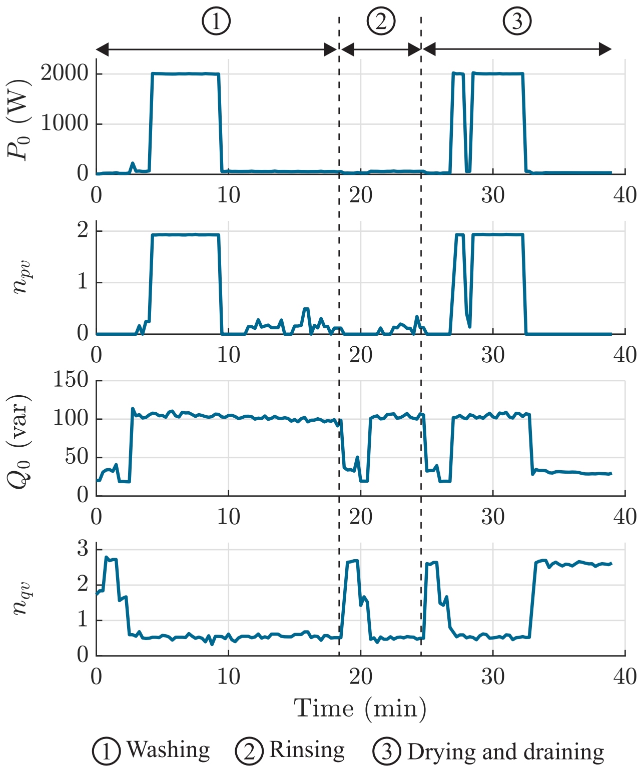

Fig. 4. Voltage sensitivity and rated power profiles of a dishwasher under quick wash mode.

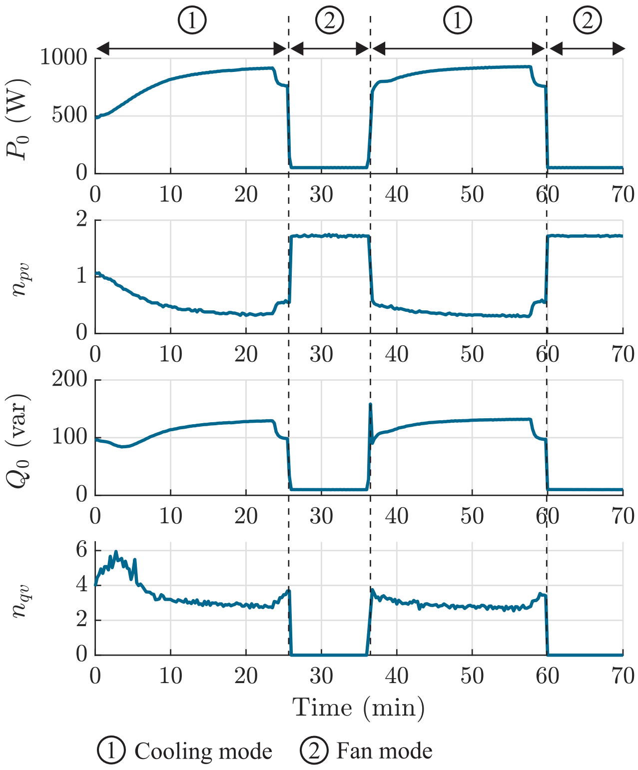

Fig. 5. Voltage sensitivity and rated power profiles of an air conditioner during the cooling cycles.

decreases dreadfully, n_{pv} remains around 2. This is due to the fact that the voltage sensitivity describes the physical characteristic of a load and the oven remains in a constant impedance behavior in both modes. The ventilator has a lower active and reactive power-to-voltage sensitivity. As the power for heating decreases, namely the impact of the ventilator increases during the heat-insulating phase, a small reduction in n_{pv} and a larger reduction in n_{qv} are observed.

4) General overview: Similar to the dishwasher and oven, many residential appliances like washing machines, cloth dryers, etc. also show large voltage sensitivity variations during an operating cycle and the time-varying characteristic shall not be ignored. Of course, there are also loads that show relatively stable voltage sensitivity profiles during the operation. An example can be seen from the sensitivity profile of a water kettle, shown in Fig. 7. However, the percentage of this kind of load decreases as more ”smart” loads are produced and used. Loads tend to have inner controllers for operational safety, energy efficiency, and user comfort improvement.

Due to space limitations, the remaining voltage sensitivity profiles cannot be presented here. However, detailed sensitivity profiles of all the tested residential loads are available with open access on GitHub [14]. Here, to provide an intuitive overview of the voltage sensitivity of tested loads, the averages of the sensitivity and rated power during the test period are presented as bar plots in Fig. 8. The loads are sorted by the active power in descending order, which is also in the descending order of the impact of n_{pv}. In total, 18 out of the 21 tested loads have active power-to-voltage sensitivity, with most showing an average n_{pv} between 0.5 and 2.0. Meanwhile, 17 loads have reactive power-to-voltage sensitivity, with most showing an average sensitivity between 0.5 and 3.0. Usually, residential appliances are designed to work normally within voltage variations of ± 10 %. Therefore, most of the tested loads have the potential of offering an average of around 5 % to 20 % active power flexibility and 5 % to 30 % of reactive power flexibility during operation.

V. VOLTAGE SENSITIVITY PROFILES OF AGGREGATED LOADS

In the previous section, voltage sensitivity profiles of individual residential appliances are determined with the perturbation-based method. The results are summarized in an open-access database. In this section, the voltage sensitivity of an apartment is studied as an example of aggregated load. In Section V-A, the perturbation-based method is used to determine the voltage sensitivity of an apartment without electrical heating. In Section V-B, the voltage sensitivity of an aggregated load is determined with both the perturbation-based method and the component-based method to verify the proposed sensitivity aggregation formula. Then, in Section V-C, the verified sensitivity aggregation formula is used to obtain the apartment voltage sensitivity profile with electrical heating.

A. One-Day Voltage Sensitivity Profile of an Apartment

In this section, the same perturbation-based method is used to identify the voltage sensitivity of an apartment. A typical daily power profile is reconstructed to present how the voltage sensitivity of an apartment varies over a day. Due to the security requirements of the ESHL, a consistent 24-hour test is not possible and is shortened to 5 hours. The identified voltage sensitivity and rated power profiles are presented

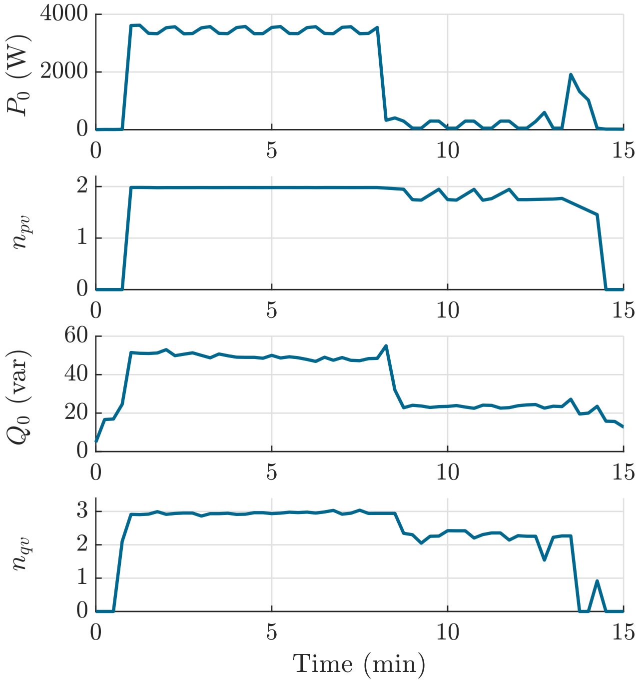

Fig. 6. Voltage sensitivity and rated power profiles of an oven baking at 280 °C with top and bottom heating.

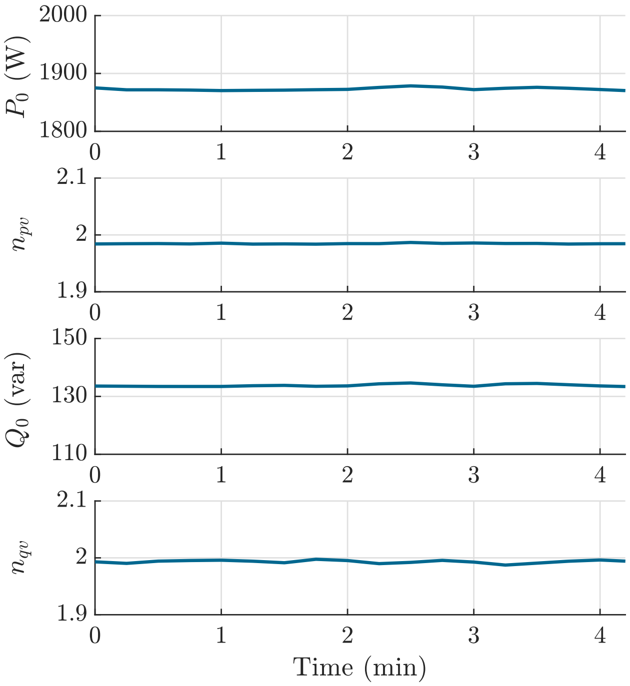

Fig. 7. Voltage sensitivity and rated power profiles of a water kettle cooking 1.5 L water.

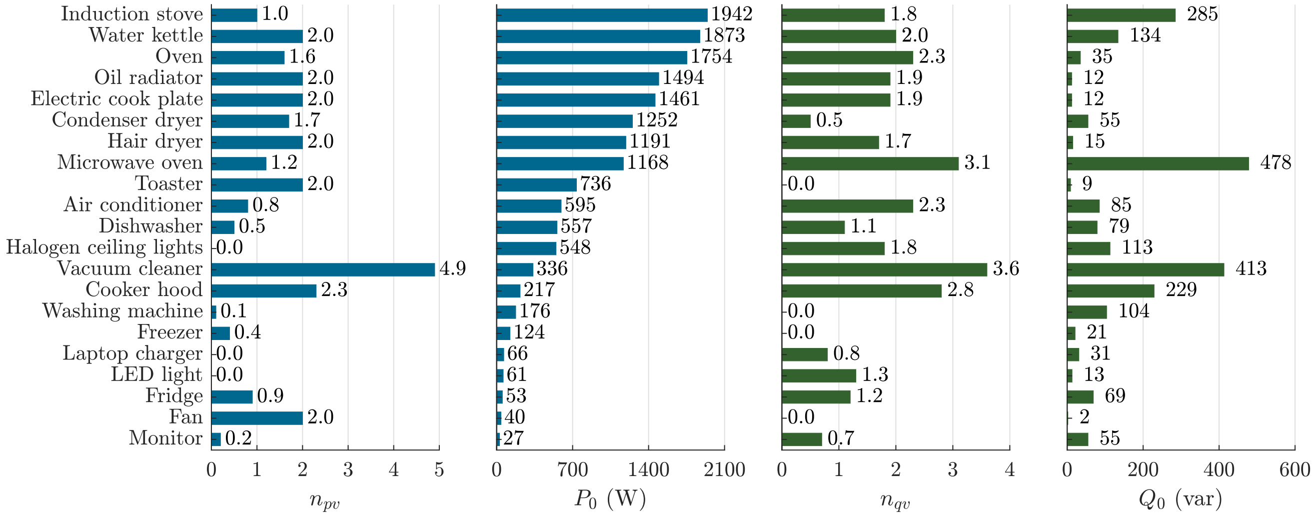

Fig. 8. Overview of voltage sensitivities and rated powers of residential loads, average values of tested operating modes.

in Fig. 9. The voltage sensitivity and rated power profiles with 15-second resolution are shown in blue, and the voltage sensitivity profiles with 15-minute resolution are shown in red, presenting how they might be seen by Distribution System Operators (DSOs).

The power consumption of the apartment is categorized into 4 scenarios: cooking, housework, away/sleeping, and rest at home. Cooking involves loads such as stoves, ovens, toasters, etc. Housework involves loads like washing machines, dishwashers, vacuum cleaners, etc. The power consumption during away and sleeping periods is similar, mainly from consistently operating appliances such as fridges, freezers, and the standby power of other devices. When the users are at home with low power consumption, such as working from home or watching TV, it is categorized as ”rest at home”.

As shown in Fig. 9, the 5-hour test can be separated into six time slots according to the power consumption scenarios, marked out with dashed lines and numbers. During the experiment, the fridge and the freezer are always running. In the first time slot, halogen lights are turned on as the users wake up. The n_{pv} stays around 0.1 and n_{qv} around 1.2. The second slot presents cooking time for breakfast, where the induction stove, water kettle, and toaster are switched on one after another. The latter two appliances are turned off after a few minutes and the induction stove operates until 7:00. The n_{pv} varies between 0.6 and 1.5 while the n_{qv} remains around 1.6. During the third time slot, the users leave for work and only the fridge and freezer are on. They consume very low active power with n_{pv} around 0.6 and n_{qv} around 1.2. During the fourth time slot, the washing machine, dishwasher, and cloth dryer operate. Due to multiple operating phases during an operating cycle, n_{pv} varies between 0.0 and 2.0 and n_{qv} varies between 0.0 and 1.5. Another cooking phase for dinner preparation occurs in the fifth time slot, during which the oven, induction stove, and cooker hood are used. The oven causes frequent and large active power and n_{pv} variation (between 0.5 and 1.8), which will not be overseen with minute range resolution. The last time slot is similar to the first slot but with fewer halogen lights on, and therefore, lower power consumption. Since the halogen lights have no voltage sensitivity, the total n_{pv} of the house is higher when the impact of halogen lights is reduced.

In the reproduced one-day power consumption experiment of a house, the active and reactive power-to-voltage sensitivity varies frequently and significantly from 0.0 to 2.0 highlighting the necessity of considering its time variance. Expanding the 5-hour results to 24 hours by assuming sleeping hours (22:00 – 06:00) and out-of-house hours (07:00 – 17:00) as repeats of the third time slot and rest at home hours (20:00 – 22:00) as repeats of the first time slot, an overall average n_{pv} of 0.7 and n_{qv} of 1.2 is obtained.

B. Verification of the Sensitivity Composition Approach

Both the measurement-based and the component-based methods can be used for the identification of the aggregated load sensitivity. Section III-E explained how the voltage sensitivity profiles of individual loads can be used to compose the sensitivity profiles of aggregated loads. The approach is verified in this section with an aggregated load consisting of three individual loads, namely an induction stove, an oven, and a cooker hood. The sensitivity of the aggregated load is determined with both methods: *i)* the measurement-based method measures the power and voltage of the aggregated load and determines the sensitivity from the measured data, shown in Fig. 10 with the blue solid line; *ii)* the component-based method measures the power and voltage of each individual load and computes their sensitivity profiles, which are then used to synthesize the sensitivity of the aggregated load according to (4), shown in Fig. 10 with the red dash line. The sensitivity profiles identified by the two methods match with each other, especially when the power is high. For accuracy purposes, the voltage sensitivity of load with power lower than 20 W or 20 var was neglected here and set to 0. Therefore, small differences can be seen between the two curves, as the

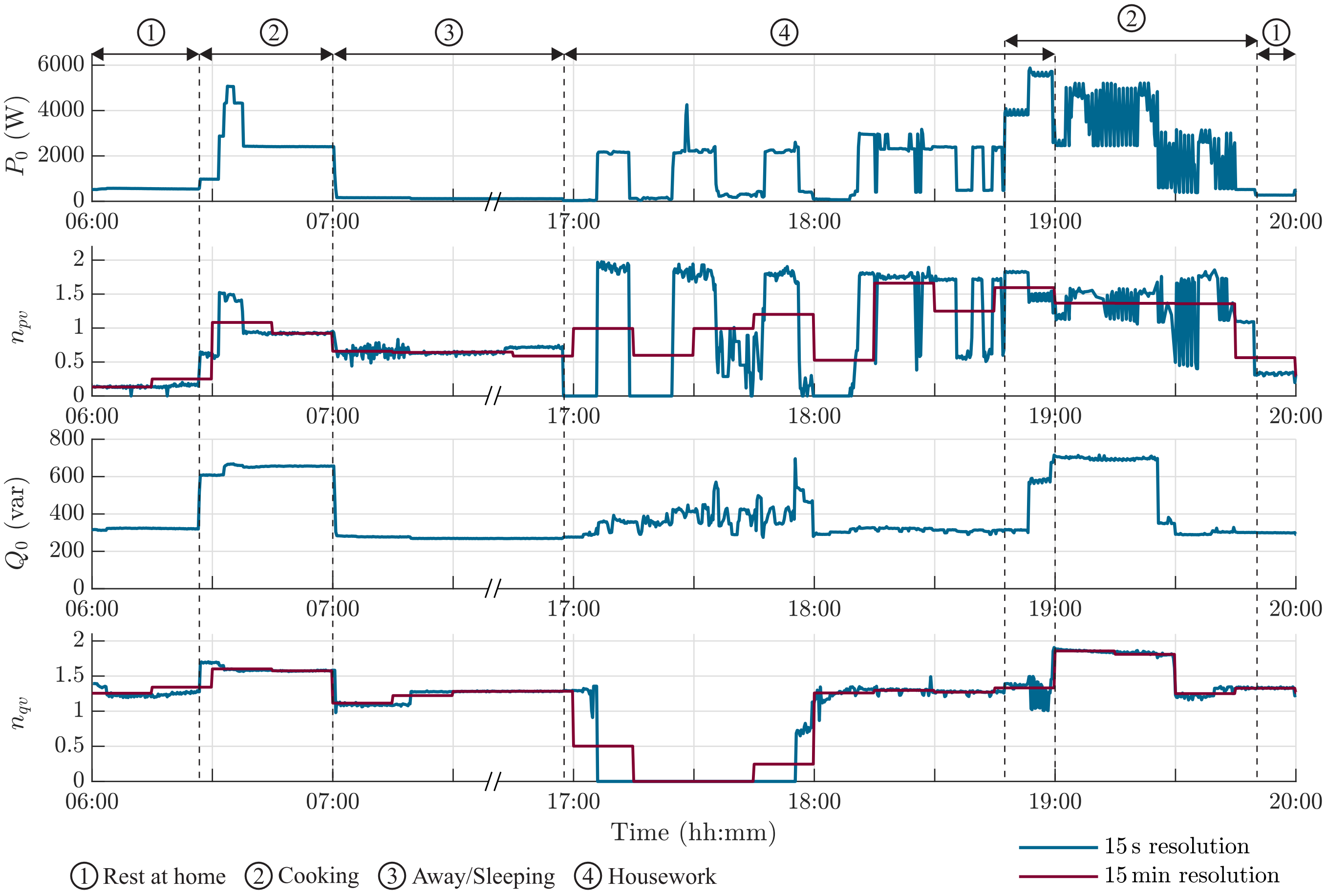

Fig. 9. Voltage sensitivity profile of an apartment over a day.

sensitivity at low power is above the limitation when the power of the load aggregation is measured.

Therefore, with the provided sensitivity and rated power database of individual appliances and the proposed sensitivity composition formula, sensitivity profiles of aggregated loads with various combinations can be obtained easily. The database and the proposed composition formula provide high flexibility in investigating the sensitivity of load aggregations, both at the component level and across the time domain. Components are not required to be tested all together and simultaneously. Voltage sensitivity profiles of domestic loads can be generated out of measurement data even without access to a laboratory.

C. The Effect of Electrical Heating

In some countries, such as Norway and France, electrical heaters are commonly used in winter. The voltage sensitivity profile in Fig. 9 does not contain an electrical heater as a load. To see the impact of using an electrical heater (oil radiator) on the voltage sensitivity profile of an apartment, the sensitivity of the oil radiator is measured and synthesized with the previous one-day sensitivity profile of the apartment. The power and voltage sensitivity profile with an electrical heater is presented in Fig. 11 in dark blue, the 15-minute average is presented in red, and the previous profile without the heater is shown in light blue. Since the reactive power of the oil radiator is very small (12 var) and below the calculation limit, n_{qv} is set to 0. Therefore, only the aggregated active power-to-voltage sensitivity profile is provided in Fig. 11.

Similar to most electrical heaters, the oil radiator can be considered as a highly resistive load with a n_{pv} equal to 2. Usually, heaters have high power consumption (e.g. 1.5 kW in our case) and thus have a big impact on the voltage sensitivity of the total apartment. As presented in Fig. 11, in comparison to the voltage sensitivity profile without the heater (light blue), the voltage sensitivity with the heater running (dark blue) shows a more stable n_{pv} value (e.g. 17:00 – 20:00). Therefore, houses that use electrical power for heating tend to have a more stable sensitivity value between 1 and 2 for a longer time during winter days. Here, only one possible example scenario is provided where the electrical heater operates at high power consistently. In reality, a heater can also work in cycles of turning on and off based on the room temperature, which results in less impact on the voltage sensitivity profile.

VI. DISCUSSION

The voltage sensitivity profiles presented in this paper are derived from measurements of specific brands and models in particular operating modes, as listed in Table II. These profiles

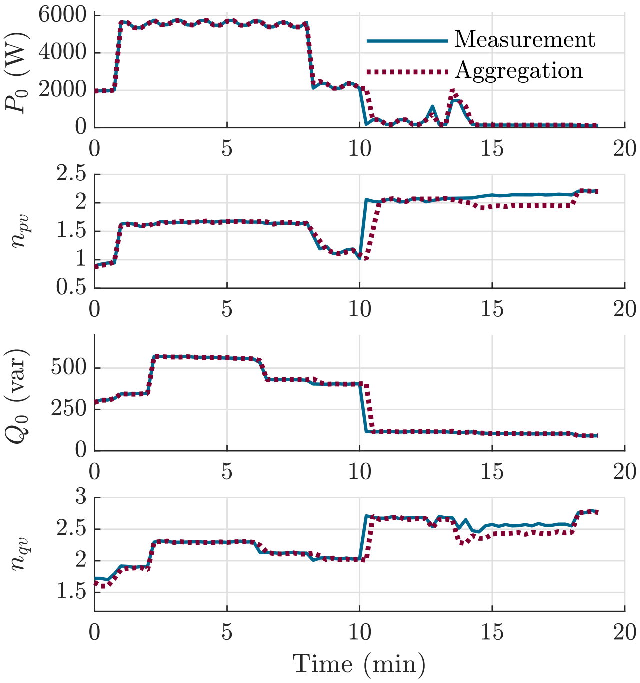

Fig. 10. Voltage sensitivities of a load aggregation composed of an induction stove, an oven, and a cooker hood.

can vary for different operating modes and models of appliances. However, the value of voltage sensitivity is determined by the main operating component and inner control logic of loads. Therefore, the voltage sensitivity profiles measured from specific appliances here can still be applied to the same type of loads with similar technologies, despite the differences in operating modes and appliance models. For instance, washing machines from various manufacturers can show similar voltage sensitivity values during the heat-up state due to the common use of resistive heating elements. This consistency can also be observed when different appliances use the same technology. For example, in Fig. 4 (4 – 10 min) and Fig. 6 (2 – 8 min), both the dishwasher and oven show n_{pv} around 2 in the heat-up state. Similarly, as mentioned in the air conditioner example, the air conditioner in the cooling state has a similar sensitivity to a freezer, and in the fan mode, it has a similar sensitivity to a fan.

Nevertheless, for appliances with similar technologies, how long a certain state lasts in an operating cycle can vary among different models and operating modes. Therefore, we provide voltage sensitivity values over time, containing sensitivity information for different states in the open-access database [14]. These sensitivity profiles allow users to adjust the duration of states as needed and to create their own operating cycles. In [29], a bottom-up load aggregation approach is proposed. The method represents the time-varying nature of residential loads concerning the probability of an appliance being on in a time slot, and the duration an appliance remains in a particular state. The same approach can also be applied to aggregate voltage sensitivity profiles for residential systems using the sensitivity data of appliances provided in this paper.

VII. CONCLUSION

This paper has investigated the time-varying nature of voltage sensitivity for residential loads. Voltage sensitivity profiles of 21 typical residential appliances are determined experimentally. The time-varying sensitivity profiles are provided with a high resolution of 15 s in a database with open access. A voltage sensitivity composition approach is proposed and validated experimentally. It enables a flexible generation of sensitivity profiles of aggregated residential loads using the experimental results of the database. Although the loads in the database are limited, they can be expanded by future researchers following the sensitivity identification guidelines.

From the sensitivity profiles, it can be seen that most residential loads show a n_{pv} between 0.5 and 2.0 and a n_{qv} between 0.5 and 3.0 most of the time during their operating cycle. Usually, residential loads are designed to be able to work normally within a voltage variation of ± 10 %. The power-to-voltage sensitivity can become 5 % to 20 % flexible active power and 5 % to 30 % flexible reactive power of the total load power consumption by voltage-led demand management. Meanwhile, the voltage sensitivity profile of a 60 m^2 apartment in the example 24 hours has an average n_{pv} of 0.7 and an average n_{qv} of 1.2, with an average active power of 1 kW and an average reactive power of 300 var (average over 24 hours). During demand peaks ($P_0 > 3$ kW or $Q_0 > 500$ var), an average active and reactive power-to-voltage sensitivity of 1.2 and 2.6 is observed. Considering the effect of using an electrical heater, the 24-hour average increases and reaches n_{pv} of 1.5.

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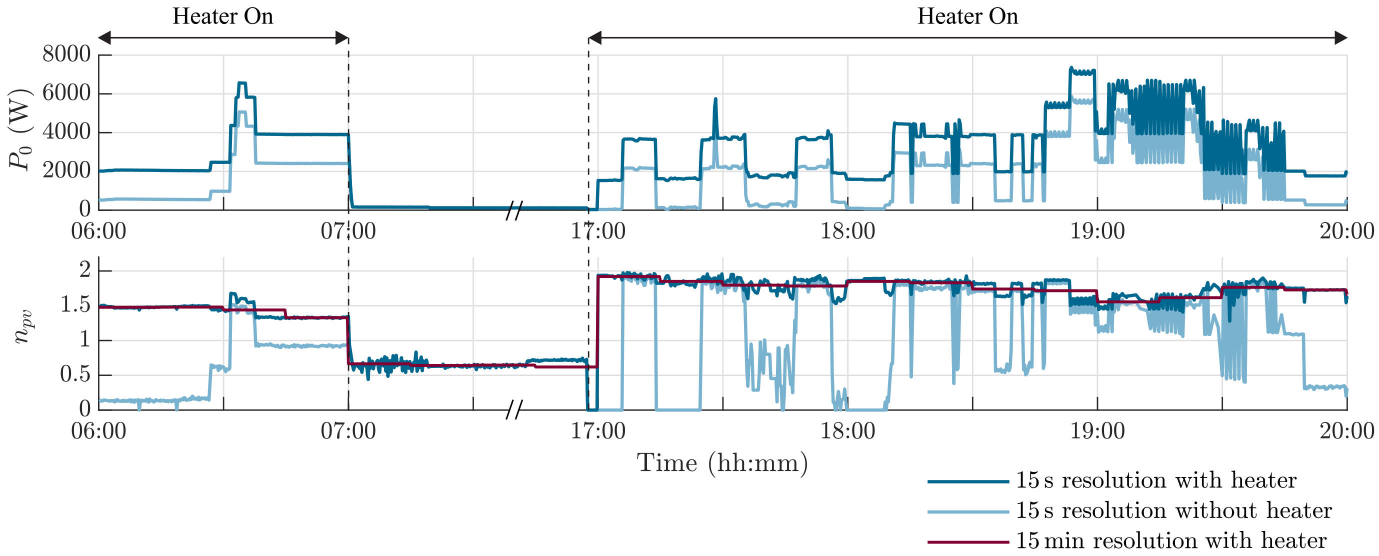

Fig. 11. Voltage sensitivity profile of an apartment with the impact of an oil radiator composed.

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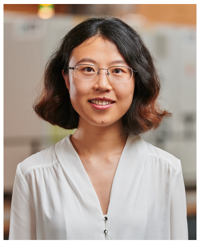

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