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Test System for Disaggregation Algorithms for use in Smart Meters

Dirk Benyoucef, Thomas Bier, Philipp Klein

Hochschule Furtwangen University, Robert-Gerwig-Platz 1, Furtwangen 78120, Germany

E-mail address: {bed, bit, p.klein}@hs-furtwangen.de

Abstract

In this paper a test system for verifying disaggregation algorithms is presented. The main part of the test system is a test set generator. Based on the model of a real voltage source, the generator generates test sets. With these test sets the quality of the developed algorithms can be analyzed. These algorithms will be developed for the implementation in a smart meter. The smart meter system is used for the disaggregation of electrical appliances in residential buildings. This allows to be closed on energy consumption of the individual appliance. The development of a complete smart meter system is the goal of the research project "Smart Metering" at the University of Furtwangen.

Keywords: Smart Meter; Non-Intrusive Appliance Load Monitoring NALM; disaggregation

1. Introduction

Saving energy is one of the most important issues of our time. Currently the user of electric devices in households only has access to information on the total energy consumption. A detailed report of the individual consumption of all appliances in the household is not yet available. The recently sold smart meters, installed at the central entry point in the household, only provide a history of the total consumption. These meters cannot provide information on active consumers and their individual energy consumption. In order to save energy users of the equipment need to change their consumption behavior, which requires more detailed electricity information. So it is important to develop a low cost energy measurement and analysis system. As part of the smart grid, another advantage of a smart meter is that it can measure the active and reactive power of appliances. With this information the utility companies can compute the power factor ($\cos(\varphi)$) with higher precision than before.

One way to provide information on individual appliances is the so called *Non-Intrusive Appliance Load Monitoring* (NALM). This means that only one measuring device is installed at the user's facility

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instead of installing a measuring device to each appliance. The identification of the individual consumers from the general consumption, the *disaggregation*, is part of that paper.

2. State of Art

The research topic NALM is divided into two areas, the steady state analysis and the transient state analysis.

The first approach for an NALM system was developed by George Hart [1]. He wanted to analyze the power consumption in residential buildings. He measured the active and reactive power in intervals of one second. Based on the delta value of the power level he concluded the switched appliance. Further work engaging the principle of Hart was carried out by Pihala [2], Murata [3], Baranski [4] and Nakano [5].

Some disadvantages of the steady state analysis can be compensated by the observation of transients. When switching on and off a device, oscillations in the waveform of voltage and current can occur. Lee found out that the sum of harmonics can reach 150% of the amplitude of the fundamental wave [6]. Work in the area of transient analysis was performed by Shaw [7] and Cox et al. [8]. A further step was performed by Lee [6] and Laughman [9] in 2003.

All of these methods use databases of individual appliances. This has the disadvantage that all devices must be included in the database during the installation of the system. A solution is to include characteristics of classes of appliances in the database. Furthermore all listed algorithms are specialized on the detection of one group of appliances. A complete system that detects all possible appliances in the load curve of private homes and that tracks their energy consumption does not exist. At this point it should be recognized.

3. The Research Project

The main goal of the research project titled "Smart Metering" is to disaggregate electrical appliances in the load curve of residential buildings. For this the project is divided into several parts [10,11]. At first a database with measurements of individual appliances was established. Currently there are 350 measurements of individual appliances in the database. From these measurements characteristics of appliances can be extracted. With these characteristics it is possible to create models of appliances. The last part is to develop algorithms, which can disaggregate the electrical appliances. Here we can distinguish three types of algorithms. The first type are *detection algorithms* (find switching-on events of appliances). The second type are *classification algorithms* (use different parameters to classify the appliances). The last type are *tracking algorithms* (track the power of the individual appliances).

4. Algorithm Development

The main part of the project consists of the development of disaggregation algorithms. With these algorithms the electrical appliances should be detected in the load profile of residential buildings. The quality of the algorithms should be verified. There are several criteria for defining the quality of developed algorithms. On the one hand the algorithms should yield a high detection rate. On the other hand they should have a low error probability.

One means for analyzing the quality of an algorithm is testing them on real signals. For this the already performed measurements in residential buildings are used. This method has a severe disadvantage: for giving a measure of error and success rate one needs to have detailed information on the switching cycles of the appliances in the household during the measurement. This information is not always available as autonomously operating appliances (e.g. refrigerators, heat pumps) do not keep record of their cycles. Additionally the documentation effort for the measurement would rise to an unacceptable level. For this reason a test system was developed. This system consists of three components and is shown in Fig. 1.

The first part of the test system is the test set generator which generates well defined and well described test sets. The advantage is that the switching cycles of appliances included in the test set are known. This way the detected events can be compared to the events in the test set. Another element of the test system is the reference algorithm. For this the well known algorithm of Hart was implemented [1]. The detection rate and the error rate of the newly developed algorithms are compared to those of the reference algorithm. This is done in the block *Compare*. This way it is possible to judge the quality of the new algorithms.

5. Test Set Generator

For the development of the test set generator, a simple model for the external grid and the appliances in the house is used. Using this model, signal characteristics of the energy consumption can be simulated. The basic idea of the test set generator is to superpose the measured individual appliances at different times.

5.1. Modeling of the external Grid

Adding the measured individual current profiles of appliances for generating superpositions will result in errors which was shown by measurements. One reason is that the mains voltage $v_L(t)$ is not constant due to the resistance of the grid lines. By switching on more and more devices Z_L the voltage drop across the internal resistance Z_S increases. This has a direct impact on the energy consumption of each appliance. When switching on a second appliance, the energy consumption of the first appliance decreases. So the instantaneous power is calculated as follows

$$p(t) = v_L(t) \cdot i(t) \qquad p(t) = v_s(t) \cdot \frac{Z_L}{Z_L + Z_s} \cdot i(t) \tag{1}$$

Secondly the measurements of the single appliance were carried out at different times. This means that the mains frequency may be different for each measurement [12].

To describe the on and off behavior of the appliances, a real voltage source was modeled. At this point the superposition is not calculated using the apparent power because of the different supply voltages and frequencies in the measurements of the individual appliance. It will be calculated by adding the admittances of the individual appliances. Using a nominal voltage, the apparent power will be calculated from these admittances. The grid can be modeled as an ideal voltage source with a voltage $v_s(t)$ connected to an admittance Y_s (internal resistance of the grid). The different appliances can be modeled as

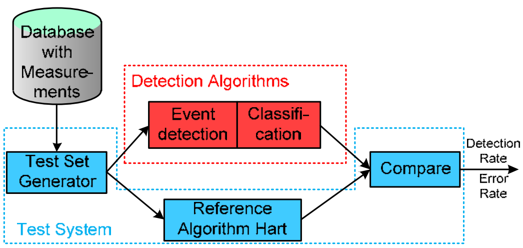

Fig. 1. Test System to verify the developed Algorithms

admittances $Y^{(1)}$ to $Y^{(M)}$ (M number of appliances). Together they form the admittance Y_L

$$Y_L = \sum_{m=1}^{M} Y^{(m)} \tag{2}$$

When dealing with at nonlinear loads distortions in the current are likely to be observed. These distortions are called harmonics. By means of the Fourier transformation all periodic signals can be represented as a sum of individual harmonic functions. Thus the current $i(t)$ is modeled as a complex current consisting of the superposition of different harmonic currents. In the following we use only the positive spectral components because of the symmetry of the spectrum. Furthermore, the number of necessary harmonics should be limited to N. Analyses of the measurements show that with the first seven harmonics a good approximation of the current waveform is achieved. This means that the current can be calculated as

$$\underline{I}(t) = I_0 + \sum_{n=1}^{N} I_n \cdot e^{j\omega_n t} \cdot e^{j\varphi_{i_n}} \tag{3}$$

The component I_0 represents the constant component (dc) of the current. I_1 is the first harmonic of the distorted current. It is the part of the fundamental wave. The components I_2 to I_N are the higher harmonics of the current. N is the N-th harmonic. The φ_{i_n} are the phase angles of the harmonics. ω_1 is the angular frequency of the fundamental wave and is calculated by $\omega_1 = 2\pi \cdot f_1$. The n-th angular frequency is a multiple of the fundamental frequency.

The mains voltage may be influenced by distortions as well. Fortunately these distortions are negligible [1,2,4]. This was also verified by the measurements performed in-house. So at this point the voltage of the appliances is modeled analogously to the current in equation (3) as

$$\underline{V_L}(t) = V_1 \cdot e^{j\omega_1 t} \cdot e^{j\varphi_{v_1}} \tag{4}$$

5.2. Modeling of non-linear appliances

For the development of the test set generator it is useful to know the individual admittances of the appliances. The admittance is calculated as the sum of the admittances at the harmonics of the current. For this the quotient of the complex current and the complex voltage is calculated.

$$\underline{Y}(t) = \frac{\sum_{n=0}^{N} \underline{I_n}(t)}{\underline{V_L}(t)} = \sum_{n=0}^{N} \frac{I_n \cdot e^{j\omega_n t} \cdot e^{j\varphi_{i_n}}}{V_1 \cdot e^{j\omega_1 t} \cdot e^{j\varphi_{v_1}}} = \sum_{n=0}^{N} Y_n \cdot e^{j(\varphi_{i_n} - \varphi_{v_1})} \cdot e^{j(\omega_n - \omega_1)t}. \tag{5}$$

Each term in the sum can now be interpreted as a source of constant frequency $(\omega_n - \omega_1)$ with admittance $Y_n \cdot e^{j(\varphi_{i_n} - \varphi_{v_1})}$. The amplitudes and the phase angles can be calculated with the Discrete Fourier Transform (DFT). In Fig. 2 and Fig. 3 two results of the simulation are shown. In Fig. 2 the simulation of a water heater, which is a linear load, is shown. In the top left corner the computed instantaneous power is plotted. The water heater has a rated power of $1600VA$. Next to this plot on the right the computed admittance of all of the individual harmonics is shown. It can be seen that all of the energy is carried by the fundamental wave. This is made clear by the sinusoidal current profile of a water heater. The two plots at the bottom of Fig. 2 show the apparent power consumed by the water heater. The lower left plot shows the apparent power of the individual harmonics, the lower right plot shows the sum of the harmonics.

In contrast to the linear load Fig. 3 shows the simulation results of a hair dryer which has nonlinear behavior and a rated power of $600VA$. As in Fig. 2 the figure shows the computed instantaneous power (top left), the individual admittances (top right), the individual apparent powers (bottom left) and the sum of the individual apparent powers (bottom right).

It can be seen that now the energy is spread over the fundamental wave and several harmonics. This is due to distortions of the sine of the current waveform.

6. Results

The generation of test sets may be done applying different parameters comprising the number of individual appliances, the number of switching events and the duration of the test set. Fig. 4 and Fig. 5 show two examples of the randomly generated superposition of appliances. The parameters were set to the following values:

- First simulation (Fig. 4): Number of appliances: 5; Number of events: 20; time: 0.5h
- Second simulation, (Fig. 5): Number of appliances: 8; Number of events: 50; time: 2.0h

7. Conclusion

The topic of this paper is the disaggregation of electric appliance in the load profile of private households. The smart meter system should be able to detect individual appliances in the aggregated electricity profile. For this reason detection algorithms are under development. After describing the state of the art and the approach of Furtwangen University a test system for evaluating developed algorithms was introduced. On the basis of a model of a real voltage source and the model of linear and nonlinear loads a test set generator was developed and presented. This test set generator generates test sets with which it is possible to verify detection algorithms. At the end simulation results of the test set generator were shown.

The next steps are to develop algorithms for the disaggregation. For this an edge detection algorithm should be develop, which find edges in the load profile of the appliances. Secondly classification algorithms are develop. Particular pattern recognition algorithms will be used. And at last a tracking algorithm should be develop, to track the working states of the appliances and calculate their energy

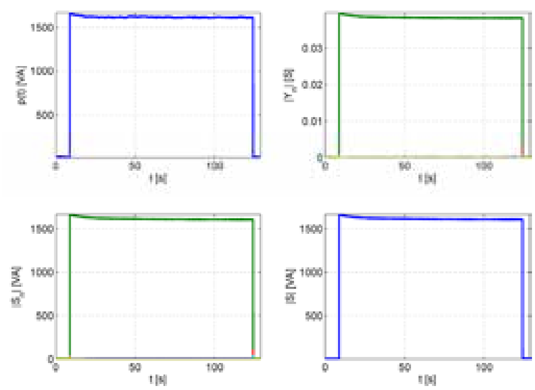

Fig. 2. Simulated signals for a linear load (water heater)

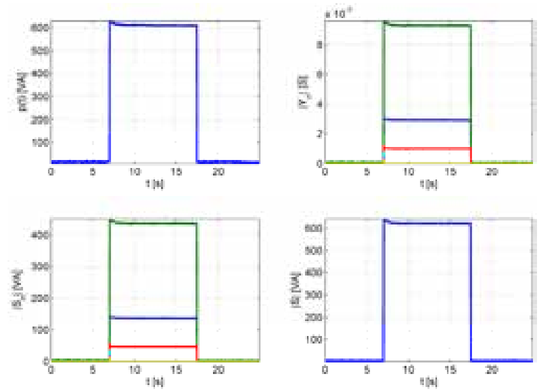

Fig. 3. Simulated signals of a hair dryer (nonlinear load)

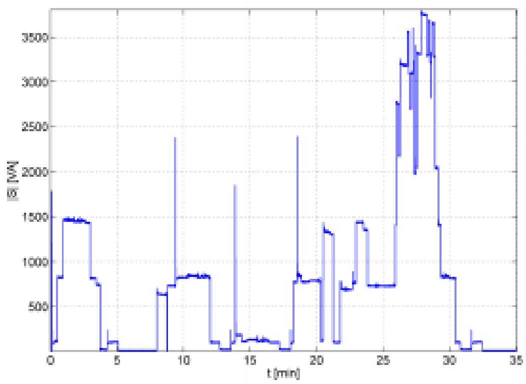

Fig. 4. Simulated superposed power with 20 events of 5 appliances

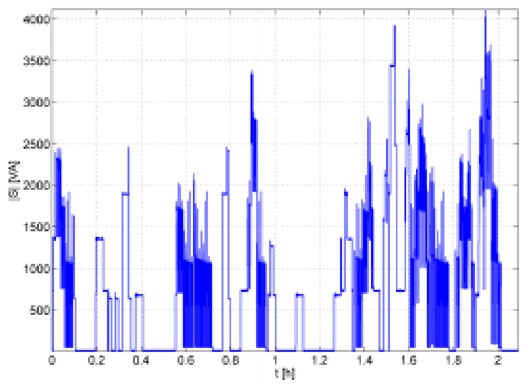

Fig. 5. Simulated superposed power with 50 events of 8 appliances

consumption.

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