High-frequency NILM and Possible Applications

Innovationsscheck-Studie

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Contents

Introduction

The goal of this work is the identification of possible applications of high frequency NILM (NonIntrusive Load Monitoring) with more emphasis on the application and less emphasis on the method. If possible the search results were screened for the frequency of the measurements in order to determine if the high frequency is really needed.

The report is structured by the main phases of the literature research. The search was done in four main phases with most time consumed in the first two phases.

The first, logical step builds on two already known NILM-surveys. Both of these two surveys were searched in depth for (i) other applications apart from NILM and (ii) applications based on NILM. Summarizing the results of this part of the research, the two survey papers are a good starting point for methodological research, their benefit for screening of possible applications of high-frequency measurements is however limited.

As a result, in the second phase further searching with Google (Scholar) was done which seemed to be more promising at this point of time. Despite various efforts papers found by Google searches only additionally yielded fault detection applications.

In order to find other kinds of applications, in the third phase the idea was to search on other companies web pages for applications. The special case of PCube was considered in more detail. While there numerous applications are listed, no details of the methods are given. Based on the statements there, it seems that the combined analysis of multiple sensors is necessary for many kinds of applications.

Finally, in the last phase, in order to have reliable and well-prepared information, various searches for books were performed. Books with promising names are listed in the last chapter.

Chapter 1

NILM Survey Papers of Zeifman and Zoha

The first starting point is the survey papers about NILM methods by Zeifman [1] and Zoha [2] and the contained publications. Both papers treat NILM methods for the disaggregation of the consumption curve into the consumption curves of different appliances. Both papers and practically all cited papers are very much focused on this particular application.

1.1 Cited Papers

The two papers only cite very few papers that do not only focus on NILM but could, according the their title, contain other applications. These papers are listed below:

- Publication [16] in [2] treats demand side management:
  Cox, Robert, et al. "Transient event detection for nonintrusive load monitoring and demand side management using voltage distortion." Applied Power Electronics Conference and Exposition, 2006. APEC'06. Twenty-First Annual IEEE. IEEE, 2006.
- Publication [75] in [2] treats the influence of user behavior
  Wood, G., and M. Newborough. "Influencing user behaviour with energy information display systems for intelligent homes." International journal of energy research 31.1 (2007): 56-78.
- Publication [77] in [2] considers NILM-results as input for a controlling unit
  Erickson, Varick L., et al. "Energy efficient building environment

control strategies using real-time occupancy measurements." Proceedings of the First ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings. ACM, 2009.

- Publication [24] in [1] is different from the previous papers in that it mentions an application that is not directly related to NILM. It is a first hint that large frequencies are important for monitoring of motors Lee, Kwangduk D., et al. "Estimation of variable-speed-drive power consumption from harmonic content." IEEE Transactions on Energy Conversion 20.3 (2005): 566-574..
- Publication [41] in [1] then directly mentions the possibility to do fault-diagnosis of engines. However, it focuses on how information from different sensors should be fused.
  Basir, Otman, and Xiaohong Yuan. "Engine fault diagnosis based on multi-sensor information fusion using Dempster–Shafer evidence theory." Information Fusion 8.4 (2007): 379-386.

1.2 Description of Features

On the methodological side, the different features that are used for analysis of high frequency signals could be of interest. These are listed below

- Harmonics or more generally the spectral envelope
- Correlation between power and different harmonics
- In contrast to the FFT, wavelets leads to information not only of the frequency but also of the time
- Geometric properties like the I-V curve
- Time-series $\frac{I(t)}{V(t)}$, $I \cdot V(t)$
- Eigenvalues of oscillation
- Transient curve when turning on or off
- Phase angle and power factor $\frac{P_{real}}{P_{apparent}}$

Additionally, there are other features like occurrence frequencies of events, data from other sensors (e.g. noise). However, these features are not assumed to be interesting for this report.

Chapter 2

Google (Scholar) searches

Various search variants were conducted using Google and Google Scholar in order to find practical applications of high frequency measurements. Nearly all results are considering applications that are essentially based on NILM methods. The small remaining part of the scientific literature treats fault detection especially of motors. This part of the report is structured by application type. The papers found were screened especially for information about the frequency of the measurements.

2.1 NILM-related applications

2.1.1 Energy disaggregation

- The first paper of Batra is a practical NILM-toolkit for energy disaggregation. Of practical interest could be in Section 3 about data set diagnostics, statistics, preprocessing and accuracy metrics.
  Batra, Nipun, et al. "NILMTK: an open source toolkit for non-intrusive load monitoring." Proceedings of the 5th international conference on Future energy systems. ACM, 2014.
- The second paper of Batra explores the differences between energy disaggregation for residential homes and commercial buildings.
  Batra, Nipun, et al. "A comparison of non-intrusive load monitoring methods for commercial and residential buildings." arXiv preprint arXiv:1408.6595 (2014).

2.1.2 Appliance Identification

The two papers of Chang [3, 4]a treat appliance identification with transient signals. Signal durations in the graphics are in the order of several times 0.1s. The method works with wavelets and neural nets.

2.1.3 Occupancy Detection

Erickson [5] treats occupancy detection which is used in order to reduce the amount of air conditioning in large buildings.

2.1.4 NILM Applications

The paper of Armel focuses on possible applications of appliance-specific information and could be a good starting point for further research.
Armel, K. Carrie, et al. "Is disaggregation the holy grail of energy efficiency? The case of electricity." Energy Policy 52 (2013): 213-234.

Given potential applications are

- Benefits to the consumer through direct feedback
  - Auto-commissioning (not clearly explained)
  - Fault detection
  - Enabling of enhanced behavioral techniques through feedback
  - Analysis of when and what type of new appliance to purchase based on current use
- R&D
  - Appliance Innovation: (a) redesign appliances for energy efficiency, (b) improved standards, and (c) back up appliance energy efficiency marketing
  - Buildings: mproved building simulation models? Commissioning.
- Energy efficiency marketing
- Improved objectivity, sensitivity, and causal inference in program evaluation?
- Performance based metrics, ratings, and incentives of buildings
- Improved load forecasting

The paper also lists requirements for disaggregation algorithms and dares to estimate the number of detectable appliances depending on the frequency

- Hourly data: 3 end-use categories (i.e., loads that correlate with outdoor temperature, loads that are continuous, and loads that are time-dependent such as pool pumps and outdoor lighting)
- 1min to 1s: 8 appliance types
- Multiple kHz range: identification of 20-40 appliance types
- MHz range: identification of potentially close to 100 distinct appliances

Finally, it explores the gap between existing solutions and what is needed, e.g. the accuracy of the AD-converter which influences the accuracy of the measurements.

2.2 Fault Detection

First, naive searches with Google with different searching terms showed surprisingly few papers that do NOT focus on the energy disaggregation application.

As a consequence, the search was performed with a possible application in mind, like fault detection. Good queries are e.g.

- fault detection induction motor

2.2.1 Fault detection of Induction Motors

The paper by Benbouzid [6] is a good starting point for fault detection of induction motors. Three types of faults are discussed

- Bearings damage
- Air gap eccentricity
- Broken rotor bar

According to this paper and that of Konar [7], bearings damage accounts for about 50% of failures. All these failures result in additional frequencies that occur in the motor current. Formulas for the frequencies are given.

The methods that are used are also briefly discussed

- Classical FFT of single-phase motor current also includes a description how the analyis system looks like.
- Instant power FFT
- The bispectrum looks like an autocorrelation function with 2 varying time lags.
- High Resolution spectral analysis with determination of the eigenvalues of the autocorrelation matrix
- Wavelet analysis has the advantage over FFT that transitory characteristics can be described (e.g. drifts, abrupt changes, frequency drifts)
- Motor Current Signature algorithm

Konar [7] use a wavelet+ANN/SVM (Artificial Neural Nets / Support Vector Machines) approach. The sampling rate of the signal is given as 7680 Hz. The paper also shows a machinery fault simulator which could be interesting.

A paper where I only read the abstract is form Sualhi. The highlight of this paper seems to be its unsupervised classification technique (artificial ant clustering).
Soualhi, Abdenour, Guy Clerc, and Hubert Razik. "Detection and diagnosis of faults in induction motor using an improved artificial ant clustering technique." IEEE Transactions on Industrial Electronics 60.9 (2013): 4053-4062.

2.2.2 Fault Detection of Airflow Handlers and Air Conditioners

This paper of Orji [8] is the first paper I found about fault detection. Although the method is based on fault detection of induction motors, it is applied to airflow handlers and therefore in its own subsection. It describes speed detection for an induction motor. The spectral envelope is used to determine when the device is turned on. The speed is calculated with the so-called principal slot harmonic frequency (Eq. (1) in the paper). This approach for estimating the speed of the motor seems to be quite common. The paper itself focuses on the determination of a frequency search window in which the maximum is taken. This approach has limited spectral accuracy for short sampling durations. An optimization method is proposed that improves the accuracy.

The method is applied for the estimation of the blockage condition of an airflow handling unit due to clogging. The speed of the fan blade is a needed input for the estimation of the histogram of the volumetric airflow of the fan. The histogram needs to be created by many starts of the fan.

This paper cites the survey of Benbouzid above.

There is also a PhD thesis of Christopher Reed Laughman from 2008 called "Fault detection methods for vapor-compression air conditioners using electrical measurements". While only the introduction is available, the references are also contained and could serve as a basis for further research.

In the PhD thesis of Cox [9], electromechanical actuators are triggered e.g. compressed air and vacuum systems are triggered by e.g. pressure or temperature. The time between pump runs in the graphics is in the order of minutes. So sampling rates of kHz do not seem to be needed for that. But maybe other systems have higher time intervals.

2.2.3 Condition Monitoring of Wind Energy Converters

The paper of Amirat [10] is very unspecific, especially the needed sampling rate is unclear.

The paper of Yang from 2010 treats condition monitoring for wind turbines. There, the sampling frequency seems to be 2kHz.
Yang, Wenxian, et al. "Cost-effective condition monitoring for wind turbines." IEEE Transactions on industrial electronics 57.1 (2010): 263-271.

2.3 Methodological Papers

Some papers do not treat applications but show methods that could be valuable for different applications.

Preprocessing is often of crucial importance for good performance of subsequent analysis tools. In 2010, Laughman introduces a Park Transform-Based Method for Condition Monitoring of Three-Phase Electromechanical Systems. The used sampling frequency was 8 kHz.
Laughman, Christopher, et al. "A park transform-based method for condition monitoring of three-phase electromechanical systems." Power Electronics, Machines and Drives (PEMD 2010), 5th IET International Conference on. IET, 2010.

The energy monitoring sensor itself is possibly only among many sensors that are for example sensing also vibrations, sound, pressure and temperature (see also the description of PCube applications). Methods for combining evidence of different sensors are then needed. Such a method is shown in [11]

Chapter 3

What Other Companies Promise

You can find competitors easily by searching for “power quality monitoring” , “power monitoring” or “power monitoring solution”. I analyzed one of these companies (PQube) and screened another (Schneider Electric). These websites are good for getting ideas for possible applications. However, they of course do not contain precise informations about the arising problems and the solutions. PQube provides limited information about the sampling rate.

3.1 PQube

Regarding PQube, a high sampling rate is needed for electric vehicle charging monitoring: “You can even use your low-cost PQube 3 to record DC voltages and currents - 30,000 samples per second is standard – providing independent confirmation of charger performance, and cross-triggered DC disturbances.” While they sometimes mention the 30kHz, this of course does not mean that it is really necessary.

The following list contains the applications they propose (which is however often not much more than the application domain).

- Find Power Problems. Save Service Costs!
  - Detect power disturbances, e.g. sags, quality of incoming power
  - Semiconductor tools
  - MRI and medical equipment
  - Data Centers - AC (and 380V DC!)
  - Telecom and Base Stations

- Use the barometric pressure sensors to detect clogged air filters.
- Shipboard power, record the ship's pitch and roll
- Large HVAC commissioning, and service, Environmental Sensors for temperature, humidity, and barometric pressure, remotely monitor
- Aircraft power and airports: monitor critical power infrastructure, like backup generators
- Pharmaceutical manufacturing
- Large power plant stability
- Distribution stability: impedances, to grid reconfiguration, to stability issues related to PV inverters, even to detect cyber attacks on substations
- Solar inverters
- Wind turbine nacelles
- Government and University Research
- Railroads and Transport: monitoring the power signature of rail switch motors, which can help predict mechanical failures and motor failures before they happen
- Electric vehicle charging: confirmation of charger performance
- Military: bases and ships

Chapter 4

Books

There already exist books on power quality monitoring or power monitoring. Here is a short list of search results

- Electrical Power Systems Quality by Roger C. Dugan and Mark F. McGranaghan
- Modern Solutions for Protection, Control and Monitoring of Electric Power Systems by Hector J. Altuve Ferrer and Edmund O. Schweitzer
- Solar Power Generation Problems, Solutions and Monitoring by Peter Gevorkian
- Operation and Maintenance of Thermal Power Stations: Best Practices and Health Monitoring (Energy Systems in Electrical Engineering) by Pradip Chanda and Suparna Mukhopaddhyay
- Interconnected Power Systems: Wide-Area Dynamic Monitoring and Control Applications by Yong Li and Dechang Yang
- Phasor Measurement Units and Wide Area Monitoring Systems by Antonello Monti and Carlo Muscas

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[11] O. Basir and X. Yuan, "Engine fault diagnosis based on multi-sensor information fusion using Dempster-Shafer evidence theory," *Information Fusion*, vol. 8, no. 4, pp. 379–386, 2007.