UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

NEW MEASURING AND MODELLING METHODS FOR DIAGNOSTICS OF ELECTRICAL CONSUMERS' DISTURBANCES AND POWER PROFILES

SUMMARY OF PHD THESIS

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DOCTORAL (PHD) THESIS BOOK OF THE UNIVERSITY OF MISKOLC
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WHO APPLIES FOR THE OBTAINING OF THE DOCTORAL (PHD) DEGREE

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1. DESIGNATION OF THE RESEARCH FIELD

High quality energy, which is energetically 'pure sinusoid', is in the interest of both consumers and suppliers. The limits of electrical network parameters have increasingly important role nowadays, since it is not only an essential component of the adequate, continuous, secure and economic operation, but in certain cases is of crucial importance in human health (e.g.: flicker phenomenon).

During my research I studied the measurement of *flicker*, one of the electrical network parameters of the standard [**1**], the most difficult to measure and define, thus I developed a new universal, online digital signal-processing methods necessary for flicker-metering. These new signal processing methods allow the identification and analysis of components and have special features from network voltage-signal. The most crucial problem is that standards regarding flicker disturbances [**2**] – although in a quite detailed way – describes one only proposal for an analogue measurement system and an analogue measurement method (even the new standards of 2010 contain a few references for sampling). Since the available standards do not deal with any requirements concerning digital proceedings (recommendations are solely dedicated to the substitution of the central component of the measurement system through a complex transfer function), the necessity of new digital methods development has arisen in the digital age.

Other achievements of the research can also be applied in network analysis as well; therefore, further examinations were carried out in the area of *centralized ripple control* (CRC). As a result of this research, network phenomena, which could hardly be analysed and handled by the supplier, became easily detectable, indicating a new trend in the future network-planning.

My research deals with solutions applicable in practice, which provide theoretical background and direct support for the supplier to control primarily heat-storage units (water heaters, storage heaters) on its network, thus intervening into the operation of the network through direct energy control.

By the application of day-time control of heat-storage equipment significant cost savings can be achieved on side both of consumers and suppliers (!), moreover, the peak and minimal values of the extreme network-load can be reduced in a justifiable way within the limits in order to reach a more balanced operation in network dispatching. Currently, it

seems that networks cannot be operated efficiently without heat-storage mass-control applied by suppliers. Based on experience, there are a number of undiscovered possibilities in heat-storage mass-control [**19**]. This research contributed at a high degree to the exploration of these opportunities and thus supports the work of suppliers.

2. SCIENTIFIC BACKGROUND OF THE RESEARCH

This research on flicker measurement showed that there are few digital, online measuring methods existing now and there are no relevant reference corresponding to my own measuring method and system. Most existing methods and algorithms are simulations only. Moreover, created modules are not and cannot be installed into a reliable and flexible measuring system. The problem with the existing measuring systems is that they are not able to provide enough flexibility in the parameters of measurement, which is crucial during the design of a universal system. Each of the possible parameter modifications is covered by the technical literature. The flexible adaptability of the sampling rate is extremely important, especially in the case of phase jumps which have been discussed only by some theoretical [**3**] and even less practical research papers [**4**]. The alterability and the fine-tuning of the flicker perception curve plays crucial role owing to the large number of today's new lights sources like energy saving and LED lamps [**5**]. Many research publications cover the necessity of the objective measurement method [**6**] which is essential to compare flicker values independent from types of lamps [**7**].

As the regulations suggest solutions mainly for the standards of flicker measurements and the way of calibration (max. errors and reference values), they offer a wide range of opportunities for the implementation of the measuring system, there are different flicker measurement methods available nowadays. In order to emphasize the complexity of methods, most research output focus on the easy problems of flicker measurements. The objective comparability of flicker measurement systems [**8**], such as the automatic and manual calibration [**9**], the error correction [**10**], the error measurements [**11**] and sensitivity of measurements [**12**] play a central role in the research work.

In the topic connected to direct energy management, my conclusion is that my work can be well adapted to latter days applied methods and algorithms. In addition, the term „*detection of heat-storage power*" has not yet existed in the technical literature. Although the bibliography refers to built-in heat-storage power, 99% of the so called daily heat-storage profiles,

estimate data which stand in the centre of research; e.g.: the heat storage profiles will be estimated from hot water consumption profiles. In most research papers the determination of direct controlled heat-storage power profiles starts from the analysis of total energy load of electrical network [**13**], which does not show the details precisely and in most cases provide inaccurate results. Physical and thermodynamical interaction analyses [**14**] and statistical modelling of controlled multiparametric networks [**15**] are frequent in research papers, therefore, can contain several errors due to the wrong starting data and reasoning processes. Instead, to prefer the multiparametric systems mentioned and stochastic state space, my technical methods deal with analyses of measurement data to in a way determine reliable the behaviour of electrical network describing different heat-storage characteristics.

Power profile forecast [**16**] and control programs optimization [**17**] are considered to be remarkable fields as well. Most of the research papers are also theoretical simulations, but pilot-projects and in some cases strategies successfully implemented even in practice can be found as well [**18**]. Appropriate time-schedule of energy consumption, by rectifying load versus time curves, moreover power profiles forecast are said to be the most acute and frequent questions of today's energy management.

In addition, new categorization of the classified heat-storage power profiles and such consumers' behaviour are key factors as well, since today's modern electric energy research leads to different SMART controls where the latest information about the consumers' attitude is necessary to develop new control strategies. In Hungary, numerous forums deal with the state-of-the-art and the trend of mass-control. Several innovative ideas show that (e.g.: [**19**]), the old and inflexible audio frequency controlled (AFCS) systems will be replaced by the flexible radio frequency controlled systems (RFCS) and SMART control systems because they contain further optimization chances and create new research motivation during the analysis of these systems.

3. AIM OF THE RESEARCH

The aim of this research was to create new algorithms, models and methods meeting the requirements of today's electrical networks' standards. In the centre of my dissertation two topics are in the focus:

- measurement of flicker parameter, that is the implementation of a new, digital, online flicker-measurement method and the comparison of the different flickermeters; in addition
- developing new analysing and evaluation methods for one-way, direct controlled heat-storage mass-control and studying of consumers' behaviour.

3.1. The aims of the flicker-research of the dissertation

The first aim is to develop a new universal, online (digital) flicker-measurement method. The implementation of a module is based on this method, the efficiency, flexibility of which compete with it, and in some cases catching up effect in today's software and hardware solutions is observed. In my dissertation special emphasis is put on the estimation of the nonlinear „lamp-eye-brain" complex transfer function which is the basis of the digital flickering method. It demonstrates the process lasting for many years, the result of which is a reliable, digital filtering method having been tested many times and being the most important element of flicker measurement.

Another aim was to develop an independent calibration method with two sub-objectives. The module developed by the author

- can be tested objectively, covering its all characteristic features. It provides an opportunity to be compared with an other flickermeter used as a black box (its calibration), moreover
- determination of optimized sampling frequency for F_1 and F_3 flicker classes according to the relevant standard.

3.2. The aim of the research centralized ripple control

The aim to develop new methods is to determine heat-storage power profiles generated centralized ripple control (CRC). By the assistance of these heat-storage power profiles, only from power consumption and instantaneous power values the behaviour of the consumers can be concluded, which means providing essential information for the power supply company.

In the dissertation recognising-, detecting-, and describing of behaviour methods was developed focusing on the measurements focused on transformers of the electric system from the point of view of heat-storage treated as a black box. As a result of my scientific research for the analysis of row data and the approximation of heat-storage profiles, the tasks are:

- to develop a universal (which can be used independently from the power company) decoder method for identifying centralized ripple control messages, then
- to develop a power detection method of high accuracy,
- to computerise of heat storage power controlled by CRC,
- to develop individual detection methods for analysing disturbances supporting the automatic evaluation of data helping automatized data analyses and essential for fast and efficient off-line data evaluation methods, moreover
- to develop a new approximation method for determination of heat-storage power profiles in such a way to compare the efficiency profiles of the independent transformers and to analyse the new consumer operation.

4. SCIENTIFIC METHODS USED DURING THE RESEARCH

4.1. Developing a new method for the approach towards the flicker perception curve

During the digital flicker measurement method modelling of nonlinear „*lamp-eye-brain*" response created by the cascade of modules of the blocks was carried out in regular succession. During the implementation the only problem was the approach to the module describing the sensitivities of human eyes. Modelling the other blocks was made according to the analogue regulations by simple mathematical signal transform and by the help of easy tuneable IIR (Infinite Impulse Response) Butterworth filters. The block describing the sensitivity of human eyes can be characterized by a complex transfer function with the behaviour of continuous time domain and this function had to be transformed into discrete time domain for digital signal processing.

The first step was to divide the complex transfer function into four parts and I approached each member with IIR filters, then by the help of their cascade I created the desired block. In this solution it was impossible to approach the special emphasis of one of the part-transfer functions with simple IIR filters precisely enough, that was the reason to search for a new solution.

After gaining solution this I used it by Fourier transform in order to weight spectra components. However, because of weighting problems discussed by the technical literature as well, I didn't use this solution. The

cascade of band-pass, high-pass and low-pass filters of the transfer function did not manage to bring the desired solution. Thus, I created the digital IIR filter by the help of bilinear discrete z-transform (Tustin-formula) which brought optimal result with its minimal error and reliable functioning.

4.2. The method suitable for adjusting the sample rate of flicker measurement in a flexible way

During the development of the new flicker measurement method I used modern measurement solutions to enable my flickermeter to choose the sampling frequency in a flexible way. To adjust of the sampling frequency accordingly is a significant factor from all aspects, because this feature enables the method to be applied for other classes of flicker measurement [**2**]. My method fulfils the demands of the most important regulations (for example: Shannon-thesis), so it does not let inappropriate adjustment of frequency either. For the flexible adjustment of the sampling frequency I use the combination of the so called anti-aliasing and downsampling methods and in this way the data processed can be easily reduced.

4.3. Online measurement method for flicker measurement

During the development of the online measuring method my important task was to define the communication interface of the flickermeter block, by which the communication between the block and its sorroundings is possible. I defined the most important tasks of the measuring method: anti-aliasing and downsampling method, flicker computation. Then I built such a modular structure between the parts that allows alterations, enlargement, and further changes possible so as to fulfil the requirements of the universality. While creating the communication interface of the modules I developed an up-to-date multitasking method adjusting to the multiprocessor systems, where the tasks are organized into two threads: data acquisition thread and flicker computation thread, providing appropriate solutions for all demands. The FIFO-based (First In First Out) communication method of the threads allowed the remarkable increase of the sample rate (≤40 kHz), which is necessary for keeping the regulations of today's flicker standards.

Compact interfaces, its modular structure and flexible adjustability of the online measurement method together are to complete the newest data acquisition tasks of today.

4.4. Objective calibration method for flickermeters testing

In case of an existing flickermeter to be tested the most important question is how to make sure about the appropriateness of the data detected when only limited amount of information is available from the manufacturers. The standards [**2**] register the flickermeter answers according to electrical network disturbances of the flickermeters and also the test requirements exactly. To solve the problem I developed an objective calibration method which is able to test and compare the joined flickermeters. The basis of the objective comparison is a signal generation method able to produce input signals according to the standards rule. Owing to the new calibration methods analyzing own and other flicker measurement methods, overall static and dynamic behaviour of flickermeter can also be investigated. This research and development provide many additional results: for example determining optimal sample rate for F1 and F3 flicker classes.

4.5. New data acquisition method for analyzing the effects of the centralized ripple control

Methods connected to centralized ripple control (CRC) determining new decoder, power detection methods and approximation of heat-storage power profiles are based on real data acquisition. After describing CRC my dissertation uses a *„reductive method"* reflecting the linear process of my research. Its first step was to develop a new data acquisition method.

Data acquisition has been made at all power substations of the North-Hungarian Region (35 stations, 46 transformers) for more than two months in order to examine definitely CRC. During data acquisition used of my own new data acquisition method for 3-7 days per transformers in average, which resulted in approximately 650 GB data from altogether 150 days spent with data acquisition. I analyzed these real results in such a way to find more information about the behaviour of the heat-storage consumers and that of the centralized ripple controlled network.

4.6. New universal decoder method

I have developed a new, universal decoder method independent from the electrical supplier. By the help of this, CRC pulses in the voltage signal can be identified precisely, determining those points of time exactly, when the electrical supplier controls power. Reliable recognition of CRC pulses is extremely important in CRC systems, since the timing of sound frequency signals shows the timing of power changes, which is one of the basic elements of heat-storage power analysis.

Recognising sound frequency pulses is made by a FFT-based (Fast Fourier Transform) sliding-window solution where the optimal frequency of the data acquisition, the size and stepping of time-window, detection level are equally important parameters discussed in the dissertation in details, demonstrating additional simulation results.

4.7. New universal power detection method

I developed a universal power detection method independent from the telegram-structure. By the help of this from the general power load data, instantaneous three-phase power the centralized ripple controlled power changes can be determined. The detecting method, after a well-selected result-percentage timebase, from the current and voltage data calculates the three-phase power values. These can be used as input data so it is able to determine the centralized ripple controlled power changes caused by control. During this process the well-selected timebase is crucial; because the elimination of the changes resulted from the stochastic behaviour of the network is possible in the most efficient way.

An entire technical solution was realized after the introduction of reaction time of signal receivers (from the point of view of the analysis it is inactive period of time) and the delay time of receivers (analysed time) and stating its optimal size. Considering these parameters and the exact location of the main pulse(s), the method is able to locate the place of the analysis of power values, by which the power changes can be determined.

4.8. Online measurement method for analysing centralized ripple controlled messages

I developed an online measurement method for the analysis of sound frequency pulses, which uses sound frequency decoder and power-detecting methods based on professional, multitasking methods, described in the previous chapter. There are three threads (data collector, decoder, detector) responsible for the developed data processing, where the harmonization of the three threads is done on FIFO memory, and on a huge data storage buffer, using the developed data communication. While developing my measurement method I created simple interfaces adjustable for any measuring and data collecting methods.

4.9. New approximation method for determination of heat-storage power profiles

A new objective profile approximation method was developed which is able to draw a curve to the daily, discrete heat-storage power data

automatically. Although my method was originally developed for the determination of heat-storage power profiles, it can also be used for generating profiles from other types of power values. My objective approximation method is based on discrete, heat-storage powers far away from each other in time, using three methods: linear approximation, FFT and inverse FFT analyses for approximation of the data. This new approximation method covers the relatively few (forty data per day) heat-storage power. The method can cope with the phenomena when the electric supplier has no power control on electrical network in the morning and in the afternoon that is there are periods of time without switching, when no data is available for the approximation.

Estimation of heat-storage profiles is a key factor for the network, as the supplier would like to know exactly in each time of the day what savings he has, on the one hand for optimization and for energy-management to avoid overloading on the other. By estimating heat-storage profiles the electrical supplier can conclude for the savings at the same time. In this dissertation I drew many other further conclusions.

4.10. Developed method for classification of consumer behaviours

I developed a new, two-phase normalisation method (easy to be automated) to compare the different transformers with different power which, on the one hand covers the difference deriving from the different power (normalization), and calculates the correction's time average of a periodic quantity for the minimization of the offset-differences of the profiles (offset correction) on the other. That is the reason why only the differences deriving from the features can be analysed between the profiles. I analysed the differences deriving from features of heat-storage profiles with absolute averaged and mean square error.

As the profile curve and the heat-storage power can be divided into three significant parts, I found useful to calculate errors for each of the three parts. This is the way when each time of the day could be examined separately.

I developed a method for the comparison of the previously normalized heat-storage profiles which resulted in the ability of categorization of the examined profiles determining new consumer behaviour for these. The comparison method resulted in general consequences being used successfully by electrical suppliers even nowadays.

5. NEW SCIENTIFIC ACHIEVEMENTS

My most important scientific results can be summarized in the following five thesis:

Thesis 1: I developed an online flicker measurement method based on purely digital principle.

The measurement method using modern multi-tasking communication solution is able to analyse the connected voltage signals online fulfilling the most severe standard requirements in connection with flickers. My developed method can be described firstly flexible because of the free selection of the sample rate of the flicker meter, secondly universal because of the possibility of alteration and further extension, thirdly applicable because of its efficient communication solutions.

Thesis 2: I developed a calibration method by which any flickermeters can be objectively and overally tested among real circumstances.

My developed method provides an overall picture about the static and dynamic operation of the connected flickermeter. According to my developed calibration method I managed to find a simulation method supporting the automatic testing able to test my online flicker measurement method entirely, and gives feedback as well, moreover, defines optimal data frequencies for the F_1 and F_3 classes flicker measurements stated in the standard requirements.

Thesis 3: I developed universal decoder and power detection methods independent from electrical supplier providing new theoretical and practical solutions in the field of power management of electrical network.

The developed methods can be used in any network where the transformers are able to define optimal sound frequency messages (telegrams) in time from primary voltage and current signals and to decode these a reliable way, and also to define the amplitude of power curves. I developed such an online measurement method which is able to detect power changes continuously using modern data communication solutions supporting individual multiprocessor systems.

Thesis 4: I developed a new approximation method able to define the mass-controlled heat-storage profiles from the detected power data of the transformers in an objective, easily automatized way.

I created a new normalization method for the comparison of the heat-storage profiles generated objectively. By this there is an opportunity to compare power profiles objectively and to ensure the application of further analysing and estimation methods.

Thesis 5: I developed a new classification method for determination of consumer behaviour which is able to categorize consumer behaviour into different classes by the help of heat-storage (normalized) profiles data.

My method compares the previously normalized heat-storage profiles with objective error-calculation concluding to the differences caused by definitely the differences between the curve-types. The new consumer groups created by the method can be described by the generally valid heat-storage profile. After validation of power requirement on one hand they result in new, generally valid consequences for heat-storage power consumers, on the other hand they make the supplier's scheduled planning more calculable and efficient.

6. UTILIZATION OF THE NEW SCIENTIFIC RESULTS

6.1. Utilization before handing in my dissertation

My online flicker-module and CRC module have been installed into a modern network diagnostic system machine developed together with my colleagues [**20**] at the *University of Miskolc, Department of Electrical and Electronic Engineering*, so after its testing in a laboratory they have been used in industrial environment as well.

Completed with the flickermeter module the network diagnostic system machine became suitable for testing all electrical network quality parameters included in the standard *MSZ EN 50160:2010* [**1**] and which is unique regarding the flexibility and adaptability of the system.

Both online modules were used in January, 2011 during the control measurements, in one of the high-capacity transformers of the Northern-Hungarian region where we were measuring for a week. The measurement plays a crucial role from the point of view of my dissertation since the winter data can be compared with the summer-winter consumers' behaviour. In addition, the completed work provides positive feedback regarding the usefulness of the developed modules as we fulfilled the request of the electrical supplier giving all necessary information about the

short- and long-term flicker level and the centralized ripple controlled power changes (values) and heating profiles.

6.2. Possible future-to-be utilizations

I proved that online flickermeter module suits the standards of today's Information Technology by its (routine) integration into a complex measurement system. The flexibility of the module is caused by the changeable sample rate (adequate with F_1 and F_3 classes) which was checked at extremely high frequencies ($\leq$40 kHz) as well. This makes the module suitable for examinations even if the demands of the later standards may become stricter. The universalism of the module is ensured by the flexibility of the main module that is the interchangeability and alterability of the IIR filter module serving the weighing curve, which is essential for the standards referring to the flicker computation method. During the designing phase of my research flexibility and universalism were in the center of my attention, because - after studying the technical literature - I realized that owing to the stricter and stricter demands of the standards the calculation methods need to be altered and final-tuned. Because of today's rapidly improving means of light sources more changes of the standards are expected, for which my method and developed modules are prepared.

As it was clear during their development, most of the flexible detecting and power profile methods and algorithms in the field of CRC can be upgraded. The generally used detecting method is applicable even in cases of radio frequency control (RFC) and SMART solutions in Hungary in the future and can serve the supplier's need. (This topic is discussed in details in this dissertation.)

The new type of normalizing and categorizing methods for defining heat-storage profiles resulted in objective-based comparison of power profiles and general consequences, which can also be useful when introducing new type of controlling strategies (RFC, SMART). The local measurements in the SMART systems have huge potentials for continuing my research as I need more data than I have presently (650 GB), for more general statements and for final-tuning the energy management.

7. ADDITIONAL RESULTS SUMMARIZED IN MY DISSERTATION

7.1. Universal, online flickermeter module (software)

I developed a software module based on my flickermeter method adapting to today's multiprocessor surroundings using data communication methods on many threads. The developed software module has been integrated into a network diagnostic software system developed together with one of my colleagues.

7.2. Calibration and test system for flicker measurements

Based on my new calibration method I worked out a signal generator software and hardware system which is suitable for overall static and dynamic testing of the flickermeters. This system generating signs omits reference signals according to the standards. By this innovation it is suitable for objective comparison between my own module and other flickermeters treated as black box.

7.3. Defining optimized sampling frequency

The developed calibrator software system provides an opportunity for inner testing of my own flickermeter as well. By the iterative implementation of the signal generating process I defined optimized sampling frequency for flicker measurement in the F_1 and F_3 classes. I tested my own module separately with setting the optimized sampling frequency.

7.4. Universal, online analyzing module

Based on sound frequency decoder and power detecting methods I created a software module by which electrical suppliers can get current information about power changes caused by sound frequency control. I installed the module into the diagnostic system of my colleague from the department. It was tested in industrial circumstances in January, 2011 as mentioned earlier. The developed module does not detect power only, but also gives analysing information for the supplier, for example sound frequency signal level.

7.5. Complex, offline analysing software

I created an individual software system which is able to analyse a tremendous amount of registered data. Due to its many functions it makes the user's analysis easier. The software contains all the information available so far about heat-storage, so professional displaying, displaying heat-storage power, determination of summaries, analysing of CRC

program's effects and comparison of the heat-storage profiles linked with normalisation are also possible.

8. THE SELECTED REFERENCES FROM THE DISSERTATION

Further references can be found in my dissertation. Because of the limited length of the thesis-booklet only the most important references are listed here.

[1] EN 50160: V*oltage characteristics of electricity supplied by public electricity networks.* 2010.

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9. MY OWN, MOST IMPORTANT PUBLICATIONS CONNECTED TO THE TOPIC OF THE DISSERTATION

The thesis-booklet contains only my most important and relevant publications. The entire list can be found in the last chapter of my dissertation.

Revised article published in a foreign language periodical

1. **A. Unhauzer**, A. Sz. Váradiné: *Online Software Module for Measurement*

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