Hardware and Software Architecture of a Smart Meter Based on Electrical Signature Analysis

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***Abstract*-The main resources used in electricity generation are becoming fewer, while the impact of renewable resources is still quite small. To allow the necessary time for the technology of renewable resources to mature, a requirement is to increase the energy efficiency. In this regard the smart grid concept was implemented, but whose efficiency depends on creation of a framework through which the end user can actively participate in the energy marketplace. End users must be able to understand how the energy is used so that they could find possibilities to increase the efficiency of energy. Within this paper the architecture of a smart system (smart meter) capable to disaggregate the whole energy consumption into individual consumers is presented. This way, the user will have a better understanding on how the energy is used, will find major consumers and will be able to reduce his consumption.**

Keywords: smart meter, nonintrusive load monitoring, energy disaggregation

I. INTRODUCTION

Electricity has become an indispensable good of the current time as it's used to power the majority of devices commonly used every day. Since its commercial use, one of the most important concerns was monitoring the electricity consumption. This was due to a certain number of reasons, such as: power quality monitoring, obtain estimates regarding the energy use or determine possibilities to reduce energy consumption [1]. Nowadays, when resources are getting increasingly scarce it's important to improve the management of both energy generation and consumption [2]. European Union decided to reduce the level of greenhouse gasses by 20%, to increase the penetration of renewable energy resources by 20% and to increase the energy efficiency by 20% by year 2020 [3]. Most of the current research was directed to increase energy efficiency of electrical devices, but this efficiency also depends on the choices the consumers make. Using time differentiated tariffs and economic incentives, utility providers have tried to determine users to shift usage to off-peak hours. With the classical electricity meters this is hard to achieve, since the information regarding the consumption is given in an abstract and unfamiliar form of the entire consumption for a specified period of time. To overcome this issue, a new type of meters was implemented, the so-called smart meters, which present the consumption in a more efficient way, in form of real-time graphs.

To increase the awareness on how the energy is consumed, smart meters can be equipped with disaggregation functions which allow them to present the consumption of each individual appliance within a house. This way, the user will have a better understanding on how the energy is used, where the inefficiencies come from and will be able to identify possibilities to improve the efficiency of energy consumption [1]. Consumption disaggregation techniques can be classified in intrusive and nonintrusive load monitoring techniques. The first one uses a network of meters, connected to each individual consumer, which send the consumption information to a central display device. The second technique uses a single meter that analyses the variations of voltage and current to determine certain events that relate with the transition of a consumer from one state to another. This technique has the advantages of a simple architecture and low cost but it requires complex software to identify the characteristics needed to detect a consumer. These characteristics represent the electrical signature and define the electrical behaviour of an individual appliance when it is operating.

The idea of nonintrusive load monitoring belongs to G.W. Hart who observed that he can see what happens within a house, in terms of appliance using, by simply analysing the variations in power consumption [4]. The algorithm identifies the consumers as finite state machines, where transitions from one state to another represent the change in the operating status. To better track variations over time, an algorithm that segments the power based on variations in current's RMS values was implemented [5].

Consumers with similar steady-state variations can generate different transient signals, when switching from one state to another. The shape of these signals depends on the physical task to be performed and can be used to detect the consumers [6-9]. These signals can be distinguished by analysing their particularities, such as: duration, amplitude, time constant, etc.

Analysis of spectral components can also be used to characterize the consumers' electrical signature [10-15]. Non-linear loads, unlike the linear loads, don't draw only currents of fundamental frequency but also currents of harmonic frequencies. Using different frequency estimation techniques [16-18] the spectral content can also be used to detect the presence of a consumer in total load. Different researchers have found that there are correspondences between the fundamental and different harmonic components [11, 15]. Using these correspondences, variable consumers can be detected and extracted from the total load.

A combination of different characteristics such as instantaneous admittance, instantaneous power, current waveform and eigenvalues was used as features to characterize the electric load signature [19-20]. Depending on the electrical structure the current waveform has different shapes from one consumer to another. Also because devices have different current consumptions the instantaneous admittance and instantaneous power can offer information about the operating status of a device. The dynamics of variable loads can be observed by applying the eigenvalue analysis of the time series of the current waveform rearranged into a matrix form.

A different approach to detect the presence of a consumer consisted in analysing the noises that occur in the electrical network [21]. It was noticed that when a consumer switches from one state to another it generates a transient signal (noise) whose spectral analysis can be used to define the consumer's electrical signature. Permanent noises (waveform distortions) were also observed during the operating state of a consumer, which can be used to detect the presence of a consumer.

In this context, the current paper describes the hardware and software architectures of a smart meter, SigMET, capable to distinguish energy consumption for each consumer. Classifying individual consumption will be achieved by a method of analysis and interpretation of different electrical characteristics. Thus, using only a single general meter, differentiation between consumers will be made based on the electrical signature. Smart meter's operation will include a calibration procedure in its installation or during its operation, when introducing a new consumer. This procedure aims to detect the consumer's electrical signature which will be stored into the smart meter's memory and further used in consumers' detection.

II. SMART METER'S ARCHITECTURE

SigMET's general architecture, which will be described in the current paper, is presented in Fig. 1. For this architecture was opted for a single data acquisition and transmission module (DAM) which has the role to transmit the measurements regarding the global consumption. Data processing for electrical energy calculation along with disaggregation of total consumption into individual consumers is achieved by the electrical signature identification algorithm (ESI) existent on the data processing module (DPM).

Basic functionalities accomplished by SigMET are: measuring the required electrical measures, data processing (measurement of global electrical energy consumption and disaggregation of total load into individual consumers), data store (data regarding the global/individual consumptions, electrical signatures database of the detected consumers and access/identification data), data communication between the modules or system's subcomponents and data display.

A. SigMET's hardware architecture

1. Block diagram of hardware system

Structurally, SigMET's hardware architecture's is composed of two main modules, DAM and DPM, each interacting with each other but also with external factors (Fig. 2).

DAM's main function is represented by the acquisition of the electrical measures of interest, while DPM's main function is to process the acquired data. Each module consists of several blocks that help in achieving the main function and other auxiliary blocks needed for the whole system to operate.

DAM blocks involved in providing the main function are:

- Signal conditioning: transforms the voltage and current levels to values compatible with the multiplexor's input;
- Multiplexor: successively connects the two channels to digital-analogue converter's input;
- Digital-analogue converter (DAC): samples, quantifies and encodes the continuous time variable voltage segments.

The blocks supporting the main function and/or have an auxiliary role are: memory, microprocessor, wireless and power line communication (PLC) and power supply.

DPM blocks involved in providing the main function are:

- Central processing unit: controls the rest of hardware devices, transmits task to each hardware component, coordinates and verifies the execution of the tasks;
- Volatile memory: space where SigMET's software applications are executed;
- Non-volatile memory: SigMET's software architecture residence.

The blocks supporting the main function and/or have an auxiliary role are: display, wireless communication, PLC communication, Ethernet communication and power supply.

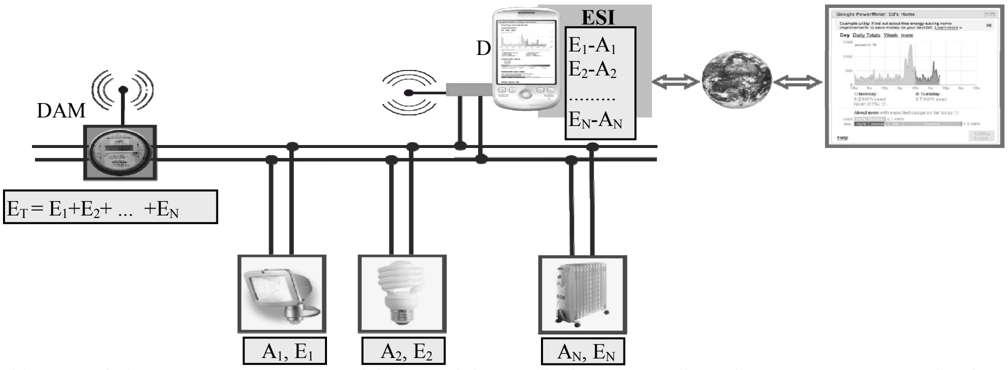


Fig. 1. General architecture of SigMET: DAM – Data Acquisition Module, D – display, A_i – appliance i, E_i – energy consumption for A_i, ESI – Electrical Signature Identification

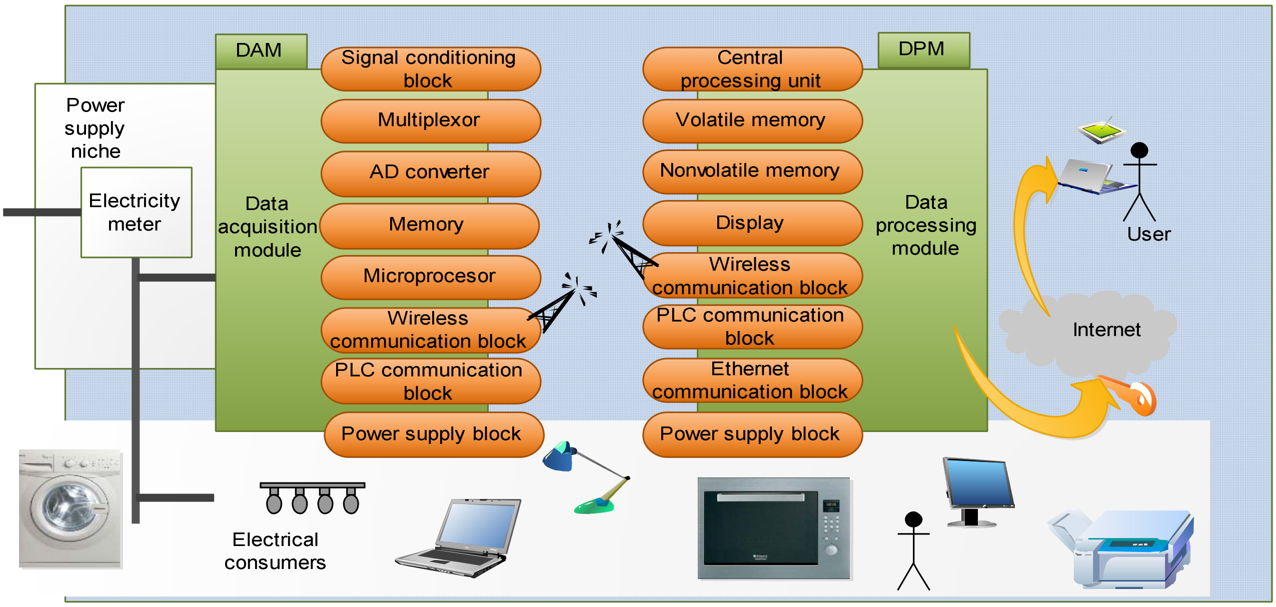


Fig. 2. SigMET's hardware architecture

2. *Operation of hardware system*

DAM is mounted in the vicinity of power supply niche to have access to the global voltage and current within the house. These parameters are measured with the signal conditioning block mounted on a rigid structure with protection against unauthorized access. Acquired data of voltage and current are transmitted, after having first been converted to digital code, to DPM. Data transmission can be made through power line communication [22-23] or radio.

At DPM level the acquired samples are numerically processed and the results are sent to the user. The information can be provided locally through the display or remotely through the internet page generated by DPM.

B. SigMET's software architecture

1. *Block diagram of software system*

SigMET's software can be seen as a system composed of multiple subsystems, each interacting with a number of other participants. The following describes the two main subsystems:

a) SigMET Server runs the DPM and is responsible for the following tasks:

- Acquisition of current and voltage waveforms from the power supply niche (data acquisition module);
- Electrical signature identification (ESI) for each consumer that contributes to the total consumption and estimation of the energy consumed by each consumer (ESI module);
- System configuration: define the consumers, work parameters, configure learning and working phases;
- Database responsible for storing and maintaining the data;
- Data server: receives the information about the electrical power of each consumer and stores it in the database, processes the data and makes reports;
- Web page: is an Web server that can be accessed on any internet browser to display the reports;
- TCP/IP comunications: is the module through which SigMET Server communicates with SigMET Client to transmit the measurement data and the reports;

b) SigMET Client is an application that runs on a mobile phone or a tablet with touch screen, through which the user has the possibility to visualize the data regarding the electricity consumption and transmit work commands to the server. It consists of the following blocks:

- TCP/IP communication module through which the client application communicates with the data server;
- Display module – responsible with the graphic display of the information to the user;
- User input: records the user commands and send them to the system;
- Data storage: allows the client application to store and access the work data;
- Data processing: processes the data to obtain the complex measurement information;
- SigMET Controller: central module that provides the communication between all application modules and is used to implement the Model View Controller (MVC) architecture.
- The participants with whom SigMET interacts are:
- End user: the user who will have the SigMET installed and which will benefit of the measurement data. For this participant, different Use Cases (UC) are attributed, by which the user interacts with the system to configure or change the work procedure.
- Internet and Wi-Fi: the participant through which the system connects to the internet network.
- Power supply niche: the point where the system collects the current and voltage data and consists of the electrical power supply wires of the building.

- Time: the participant that synchronizes the system and is used in measuring and periodic transmission of the energy consumptions.

C. *Service Orientated Architecture (SOA)*

For SigMET's software component a service-oriented architecture is used, where the services are code segments that perform certain tasks and can be reused within the system to resolve different tasks. SOA isn't an actual API (Application Programming Interface), but it rather defines the interface between the software components, based on protocols and functionality. Within SOA there are suppliers and consumers. The services will communicate with each other through a well defined dataset, visible throughout the application.

The advantage of this architecture is that services aren't connected with each other and can be developed and tested independently of each other. This allows the teams of programmers to work in parallel, test their services and after that to integrate them into the final system.

In SigMET system, each subsystem can be seen as a set of services associated with an UC. The services will be implemented separately, tested using specific test cases (TC) and integrated in the final application. For SigMET Server the following services are attributed: waveform acquisition, consumer's electrical signature identification, database storage, data processing and reporting, TCP/IP data transmission, Web page display and system configuration. For SigMET Client the following services are attributed: data display, TCP/IP data transmission, data processing and store and system setup.

D. *Architecture of electrical signature identification system*

Electrical signature can be defined as a set of electrical parameters which can be used to detect the operating status of an electrical consumer at a time. The parameters that can characterize the electrical signature are: active and reactive power changes, current's harmonics, instantaneous power, admittance, phase shift between voltage and current or current's waveform.

Using the sensorial part of the SigMET the current and voltage are measured and conditioned to compatible levels. Using these signals the algorithm proceeds to the next stage, the event detection. An event can be defined as a consistent change of the parameters of interest, which can be determined by the transition of a consumer from one state to another. Detection of these changes is made based on predefined thresholds, whose values must be high enough to not detect false events, but also low enough to detect the smaller consumers. Transient events that aren't caused by switching a consumer will be eliminated.

The parameters used to define the electrical signature will be determined only if an event is detected. This avoids loading the algorithm with a set of operations that are not necessary when no consumers are switched. The parameters which can be used are: phase shift between current and voltage, active and reactive power changes or current's harmonics.

Depending on the consumer's electrical structure the phase shift between the current and voltage can take different values. For resistive consumers the phase shift is 90º while for other types of consumers, depending on the inductive or capacitive components used, the phase shift will take different values that can be used in consumers' detection.

A consumer's switch is accompanied by different changes in the energy consumption. These changes are different from one consumer to another, and so may be used in consumer detection. It is therefore useful to calculate the active and reactive powers. Both powers are used as may be consumers who determine similar changes of one power but totally different of the other one.

Depending on their electrical components, the consumers can draw currents both at fundamental frequency and at higher harmonic frequencies. Spectral content can differ from one consumer to another, thus it is also useful to determine the harmonic components of the drawn current. A study on different consumer categories is required, to determine the highest harmonic that can cause substantial changes. Through this study the algorithm will be optimized so that it will determine only the part of interest from the spectral spectrum.

It's important that measured parameters follow as closely as possible the variations that occur when a consumer switches from one state to another. Of the two measured signals, the current is the one that varies when a consumer is switched. Taking this into account, the algorithm must be implemented so that the analyzed parameters are calculated when consistent changes of the current occur.

Detected events can be analyzed both in steady state and transient regime. Therefore, an event will be characterized by the changes of the analyzed parameters and their transient profile recorded when a consumer switches from one state to another. Taking into account that transient signals can vary from milliseconds to seconds, the algorithms must be implemented so they can adapt to these variations. For example, transient signals for resistive consumers may be missing or have a very short duration, while pump operated devices can have long transient signals. The algorithm must take into account this fact; it must be able to analyze the data at high frequencies for long periods of time.

Based on detected events, the algorithm will proceed with the electrical signature identification which corresponds with consumers' detection. For this, a database that contains the consumers' electrical signatures is required. This database can be made at the beginning during a learning stage or on the way while different electrical signatures are detected. The first version presents the following advantages:

- Detected electrical signatures will take average values of a consumer operating status, thus reducing the risk for an electrical signature to belong to a particular case;
- An equivalence between an electrical signature and a consumer can be made (consumers' naming can be made);
- Multi-state consumers can be identified correctly, avoiding situations where states of these consumers can be assigned to different consumers.

This version presents and disadvantages:

- The implemented algorithm is not autonomous – depends of this learning stage that will be done by a qualified operator;
- Problems can occur when consumers that weren't previously defined are detected.

The second version presents the following advantages:

- The implemented algorithm is autonomous, won't require the intervention of qualified personnel;
- It can adapt to different environments, it doesn't require a previously configuration.

This also presents disadvantages:

- There is the possibility that a multi-state consumer determine detection of other consumers with similar parameter changes;
- Initial detection of a consumer may correspond to a particular situation, so that future switches of the same consumer determine detection of different consumers;
- Difficulties regarding the consumers' naming.

Within the second version the initial consumers' detection can be made based on the principle that the sum of all power changes, determined by an electrical consumer during an off-on-off cycle, is zero or close to zero. Using the database generated through the consumers' input interface, the algorithm will proceed with the consumers' detection. This consists in searching in the database consumers who have the same parameters with the electrical signature of the current detected event.

In practice there may be situations where two or more consumers are switched at the same time. For this purpose, a routine that takes into account these situations will be implemented. When for a transition no consumer is identified, this routine will generate combinations of consumers to determine if that transition can be determined by the simultaneous switch of several consumers.

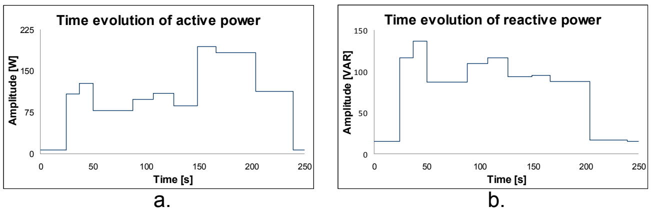
A routine will also be implemented that will take into account the values of the parameters when no consumer is turned on. When this level is achieved, the operating states of all detected consumers are analyzed. If a consumer is found to be turned on then automatically it will be switched to off state. The transitions that determined the on state for the consumers found as turned on will be reviewed in order to determine if they could have been caused by a new consumer.

As consumers are identified, the overall consumption is broken down into consumptions for each individual consumer. These values are recorded into a database and will be used for statistical reports. Also this information will be provided to the user through a graphic interface.

III. EXPERIMENTAL DATA

The following experimental data will present the principle of consumers' detection based on their electrical signature. The parameters which will be analysed to determine the electrical signatures are the variations in time of active and reactive powers. In Fig. 3 is presented the evolution of active and reactive powers when 4 different consumers are switched from one state to another. Data shown are obtained after a previously segmentation was performed to separate the steady states from the transient states. For a better analysis of the experimental data and a better understanding how the consumers' detection is achieved, active and reactive power changes (ΔP and ΔQ) are presented in Table 1. Since no consumer was previously detected, new consumers will be detected and their electrical signature will be stored in the database. The second version of database generation is chosen because it's autonomous and doesn't require any external intervention. As stated before, the initial consumers' detection is made on the principle that the sum of all power changes, determined by a consumer during an off-on-off cycle, is zero or close to zero. The parameters of transient profiles that have not been assigned to any device are recorded into the $\boldsymbol{\Delta P}$ and $\boldsymbol{\Delta Q}$ vectors. As new transient profiles are detected the corresponding power changes are compared with different combinations made with the items of $\boldsymbol{\Delta P}$ and $\boldsymbol{\Delta Q}$ vectors. Since the values of the power changes are affected by measurement and calculation errors, thresholds are taken into consideration when the comparison is performed: $\Delta P_{thr+} = |\Delta P| \times 110\% + l_{fa}$, $\Delta P_{thr-} = |\Delta P| \times 90\% - l_{fa}$, $\Delta Q_{thr+} = |\Delta Q| \times 110\% + l_{fr}$, $\Delta Q_{thr-} = |\Delta Q| \times 90\% - l_{fr}$, where l_{fa} and l_{fr} are fixed additional limits for the active and reactive power changes. These limits are added to take into account the variations that occur on small power changes and determine a percentage variation larger than 10%. For example an incandescent bulb determines a small reactive power change of the order of a few VAR's. If one time determines a power change of 1 VAR and another time a power change of 2 VAR, is obvious that the 10% limit isn't enough. Thus, the two additional limits are used, and their values are chosen to 1 W for l_{fa} and 5 VAR for l_{fr}. The higher value for l_{fr} was chosen, since from the experimental research, higher variations were observed in the case of the reactive power changes.

From Table 1 it can be seen that, until the seventh state (t = 126 s) no consumer is detected, since no combination of power changes is found within the predefined limits. For the 7th state the following limits are calculated: $\Delta P_{prag-} = |-22.51| \times 90\% = 20.26$ W, $\Delta P_{prag+} = |-22.51| \times 110\% = 24.76$ W, $\Delta Q_{prag-} = |-23.63| \times 90\% - 5 = 16.27$ VAR, $\Delta Q_{prag+} = |-23.63| \times 110\% + 5 = 30.99$ VAR. Each of the undefined vectors contains 5 elements, which can be used to generate 31 combinations. Among them, only one falls within the limits: 20.44 W and 22.13 VAR corresponding to the 5th state. Since no consumer is registered in the database, it is considered that a new consumer was detected, whose information will be recorded in the database.



a.   b.

Figure 3. Evolution of powers generated by switching on and off 4 consumers: a. active power evolution; b. reactive power evolution

TABLE I
EVOLUTION OF POWER CHANGES AND CONSUMER DETECTION PROCESS

No.	t_{start} ^{a} [s]	ΔP [W]	ΔQ [VAR]	$\mathbf{\Delta P}$ [W]	$\mathbf{\Delta Q}$ [VAR]	Detected consumer [W, VAR]
1.	0	7.14	15.33	[ ]	[ ]	-
2.	24	101.48	100.91	[101.48]	[100.91]	-
3.	37	18.65	20.45	[101.48, 18.65]	[100.91, 20.45]	-
4.	50	-49.75	-49.68	[101.48, 18.65, -49.75]	[100.91, 20.45, -49.68]	-
5.	88	20.44	22.13	[101.48, 18.65, -49.75, 20.44]	[100.91, 20.45, -49.68, 22.13]	-
6.	107	10.22	7.17	[101.48, 18.65, -49.75, 20.44, 10.22]	[100.91, 20.45, -49.68, 22.13, 7.17]	-
7.	126	-22.51	-23.63	[101.48, 18.65, -49.75, 10.22]	[100.91, 20.45, -49.68, 7.17]	[21.48, 22.88]
8.	149	106.69	0.98	[101.48, 18.65, -49.75, 10.22, 106.69]	[100.91, 20.45, -49.68, 7.17, 0.98]	-
9.	166	-10.89	-8.14	[101.48, 18.65, -49.75, 106.69]	[100.91, 20.45, -49.68, 0.98]	[10.55, 7.65]
10.	204	-70.24	-71.10	[106.69]	[0.98]	[120.13, 121.35]
11.	240	-106.48	-1.32	[ ]	[ ]	[106.58, 1.15]

^{a}Start time of the current power change

The algorithm continues similarly to analyse all the states, and thus other 3 new consumers are detected, as it can be seen in "Detected consumer" column from Table 3.1.

IV. CONCLUSIONS

In this paper the architecture of a smart meter was presented. Unlike a classic electricity meter the smart meter offers a more detailed package of information about the electricity consumption. The information is offered in real-time in a more familiar way, in form of graphs, not as abstract as in the case of the classic meter that offers a single value about the whole consumption at a time. Also the information about the consumption is disaggregated into individual consumers, which offers the user a clearer view about how the energy is used. The user will have a better understanding about his energy use, will know which are the major consumers, how and when they consume energy. This gives the user the ability to find possibilities to improve his energy use which will lead to a reduction in his carbon footprint and also in consumption of resources used in electricity generation.

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REFERENCES

[1] T. Ueno, R. Inada,O. Saeki, and K. Tsuji, "Effectiveness of displaying energy consumption data in residential houses. Analysis of how the residents respond," *ECEEE 2005 Summer Study Proc.*, vol. 3, pp. 1289-1301, 2005.

[2] A.S. Ardeleanu, M. Cretu, and C. Donciu, "Electrical signature – a means of improving the management of electricity consumers," *Proc. of the 7th Int. Conf. on Manag. of Technol. Changes*, vol. 2, pp. 553-556, 2011.

[3] World Business Council for Sustainable Development, "Energy efficiency in buildings: Business realities and opportunities," Technical report, 2008.

[4] G.W. Hart, "Nonintrusive appliance load monitoring," *Proc. of the IEEE*, vol. 80, pp. 1870-1891, 1992.

[5] A.S. Ardeleanu, C. Donciu, "Nonintrusive load detection algorithm based on variations in power consumption," *Proc. of the 2012 Int. Conf. and Exp. on Electrical and Pow. Eng.*, pp. 792-797, 2012.

[6] S.B. Leeb, and J.L. Kirtley, "A multiscale transient event detector for nonintrusive load monitoring," *Proceedings of the IECON*, vol. 1, pp. 354-359, 1993.

[7] L.K. Norford, and S.B. Leeb, "Non-intrusive electrical load monitoring in commercial buildings based on steady-state and transient load-detection algorithms," *Energ. Buildings*, vol. 24, pp. 51-64, 1996.

[8] U.A. Khan, S.B. Lee, and M.C. Lee, "A multiprocessor for transient event detection," *IEEE T. Power Deliver.*, vol. 12, pp. 51-60, 1997.

[9] H.H. Chang, C.L. Lin, and J.K. Lee, "Load Identification in Nonintrusive Load Monitoring Using Steady-State and Turn-on Transient Energy Algorithms," *Proc. of the 2010 14th Int. Conf. on Computer Supported Cooperative Work in Design*, pp. 27-32, 2010.

[10] A.I. Cole, and A. Albicki, "Nonintrusive identification of electrical loads in a three-phase environment based on harmonic content," *Proc. of the IEEE IMTC Conf.*, pp. 24–29, 2010.

[11] K.D. Lee, S.B. Leeb, L.K. Norford, P.R. Armstrong, J. Holloway, et al., "Estimation of variable-speed-drive power consumption from harmonic content," *IEEE T Energy Conver.*, vol. 20, pp. 566-574, 2005.

[12] D. Srinivasan, W.S. Ng, and A.C. Liew, "Neural-network-based signature recognition for harmonic source identification," *IEEE T. Power Deliver.*, vol. 21, pp. 398-405, 2006.

[13] C. Laughman, K. Lee, R. Cox, S. Shaw, S. Leeb, et al., "Power Signature Analysis," *IEEE Power Energy M.*, vol. 1, pp. 56-63, 2003.

[14] S.R. Shaw, S.B. Leeb, L.K. Norfold, and R.W. Cox, "Nonintrusive Load Monitoring and Diagnostics in Power Systems," *IEEE T. Instrum. Meas.*, vol. 57, pp. 1445-1454, 2008.

[15] W. Wichakool, A.T. Avestruz, R.W. Cox, and S.B. Leeb, "Modeling and Estimating Current Harmonics of Variable Electronic Loads," *IEEE T. Power Electr.*, vol. 24, pp. 2803-2811, 2009.

[16] A.S. Ardeleanu, C. Donciu, "Frequency estimation based on variable frequency resolution concept," *Proc. of the 2012 Int. Conf. and Exp. on Electrical and Pow. Eng.*, pp. 309-313, 2012.

[17] C. Donciu, C. Temneanu, and R. Ciobanu, "Breaking Nyquist criteria using alias frequencies interpretation," *Proc. of the 2005 IEEE Int. Conf. on Virtual Environments, Human Computer Interfaces and Measurement Systems,* 2005.

[18] C. Temneanu, C. Donciu, R. Ciobanu, and C. Schreiner, "Minimal fuzzy logic controller, design considerations and potential applications," *IEEE Int. Conf. on Computational Intelligence for Measurement Systems and Applications*, pp. 141-144, 2005.

[19] J. Liang, S.K.K. Ng, G. Kendall, and J.W.M. Cheng, "Load Signature Study—Part I: Basic Concept, Structure, and Methodology," *IEEE T. Power Deliver.*, vol. 25, pp. 551-560, 2010.

[20] J. Liang, S.K.K. Ng, G. Kendall, and J.W.M. Cheng, "Load Signature Study-Part II: Disaggregation, Framework, Simulation, and Applications," *IEEE T. Power Deliver.*, vol. 25, pp. 561-569, 2010.

[21] S.N. Patel, T. Robertson, J.A. Kientz, M.S. Reynolds, G.D. Abowd, "At the flick of a switch: detecting and classifying unique electrical events on the residential power line," *Proc. of the 9th Int. Conf. on Ubiquitous computing*, pp. 271-288, 2007.

[22] C. Donciu, and O. Costea, "Intelligent system for precision irrigation of greenhouse vegetables," *Proc. of 6th Int. Conf. on Manag. of Technol. Changes*, vol. 2, pp. 669-672, 2009.

[23] C. Donciu, O. Costea, M. Temneanu, R. Damian, and M. Branzila, "New prototype architecture for automated irrigation based on power line communication," *Grid Enable Remote Instrumentation*, pp. 499-509, 2009.