ELSEVIER
CrossMark
Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 61 (2014) 146 – 150
Energy Procedia

The 6th International Conference on Applied Energy – ICAE2014

A Non-Intrusive Load Monitoring System Using an Embedded System for Applications to Unbalanced Residential Distribution Systems

Hsueh-Hsien Chang[a,] *, Putu Wegadiputra Wiratha[b], Nanming Chen[b]

[a]Jin-Wen University of Science and Technology, No.99, Anzhong Rd., Xindian Dist., New Taipei City 23154, Taiwan
[b]National Taiwan University of Science and Technology, No.43, Sec. 4, Keelung Rd., Da'an Dist., Taipei 106, Taiwan

Abstract

A Non-intrusive load monitoring (NILM) system is an energy demand monitoring and load identification system that only uses voltage and current sensors that are installed at the power service entrance of an electric system. The system is better than traditional intrusive monitoring systems because it is able to reduce the cost of sensors and installations. In this study, a real single-phase three-wire unbalanced 220V/110V distribution system model of a residential building is designed and implemented, and some non-intrusive techniques are executed in the Intel Atom Embedded System and a LabView program. To enhance the performance, the paper proposes using Particle Swarm Optimization (PSO) algorithm to optimize the parameters of a Back-propagation Artificial Neural Network (BP-ANN) for training steady-state power signatures such as real and reactive power (PQ). In this paper, the NILM system can identify some major appliances correctly in an unbalanced 220V/110V distribution system of a residential building. The real test identification accuracy can reach 100%.

Peer-review under responsibility of the Organizing Committee of ICAE2014

Keywords: Non-intrusive load monitoring (NILM); embedded systems; particle swarm optimization (PSO); unbalanced distribution system; back-propagation artificial neural network (BP-ANN)

1. Introduction

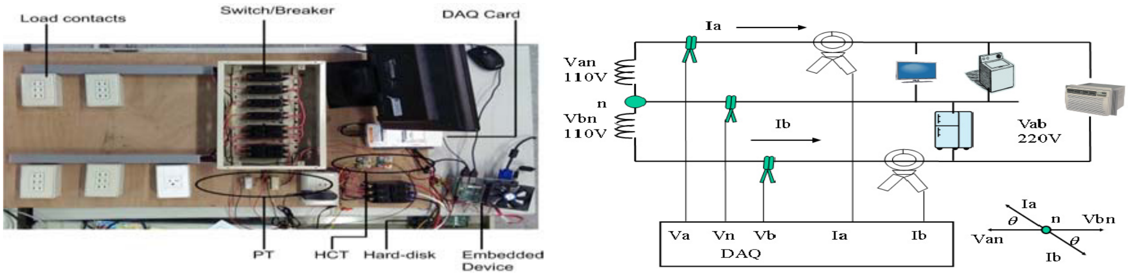
In a power system, there are usually some sensors installed in each load to monitor the energy consumption and to indentify load status. This method is called intrusive load monitoring system. Non-intrusive load monitoring systems (NILM) can drastically reduce hardware and maintenance costs because only one set of voltage and current sensors are needed at the electrical service entry (ESE). By

* Corresponding author. Tel.: +886-2-82122000; fax: +886-8212-2801.
E-mail address: sschang@just.edu.tw.

Peer-review under responsibility of the Organizing Committee of ICAE2014
doi:10.1016/j.egypro.2014.11.926

analyzing voltage and current waveforms, the NILM system can estimate the number and the nature of individual loads, and their energy consumption [1, 2]. One of the earliest studies about the NILM system was developed in 1980s by Fred Schweppe and George W. Hart. It was used in load monitoring techniques for balanced distribution systems of residential buildings based on steady-state values [3]. There are also some references of studies that proposed some methods to extract and select power signatures for improving the identification accuracy such as turn-on transient energy, power spectrum of the Wavelet transform coefficients (WTCs) etc. [4, 5].

The NILM system of an unbalanced single-phase three-wire distribution system for residual buildings is demonstrated in Fig. 1. The potential transformer (PT) in the system is a traditional PT. A Hall current transformer is used to replace traditional iron cored current transformer (CT) to reduce the space of instruments and to avoid saturation of traditional CT. In this paper, an embedded system is employed for the meter database management system (MDMS).



(a) (b)

Fig. 1. Load identification system, (a) NILM system; (b) the unbalanced single-phase three-wire distribution system

2. Proposed Methods

2.1. Power Signatures

For steady-state linear time-invariant loads, complex power can be calculated from voltage, current, and phase angles. In Eq. 1, the real part of the apparent power (*S*) is the real power (*P*) or average power and the imaginary part is the reactive power (*Q*). They can be computed by

$$S = \frac{1}{2} V \bar{I} = \frac{1}{2} V_m I_m e^{j(\theta_v - \theta_I)} = P + jQ \tag{1}$$

$$P = V_0 I_0 + \sum_{n=1}^{N} V_n I_n \sin(\theta_{V_n} - \theta_{I_n}) \tag{2}$$

$$Q = \sum_{n=1}^{N} V_n I_n \sin(\theta_{V_n} - \theta_{I_n}) \tag{3}$$

where the variables V_m and I_m are the maximum value of voltage and current, respectively; θ_V and θ_I are the phase angles of voltage and current, respectively. The variable *n* is the frequency number with $n = 0, 1, 2, \ldots, N$. The variables V_0 and I_0 are the DC voltage and current while V_n and I_n are the effective *n*th harmonic components of the voltage and current. The variables θ_{Vn} and θ_{In} represent the phase angles of the *n*th harmonic components of voltage and current, respectively.

2.2. Particle Swarm Optimization

Some researchers have used Genetic Algorithm (GA) to find sets of weights and thresholds of ANNs, but migration among sub-species of machines will be a problem due to GA crossover. To mitigate the disadvantages of the GA, a method for load identification of the NILM system is proposed in this paper. This method applies Particle swarm optimization (PSO) to optimize the parameters of training algorithms in ANN and to find the optimum solution of load pattern recognition for traditional steady-state power signatures by updating the velocity and location of particles. Moreover, it is expected that the identification accuracy can be better than only using neural network as in conventional methods.

Particle swarm optimization algorithm always begins with initializing the population of particles. Each particle is provided with a random location and velocity. The fitness of a particle is evaluated and updated in each iteration [6]. There are terms of p_{Best} and g_{Best} in this algorithm. The p_{Best} is the best location fitness value (individually), while g_{Best} is the global best solution among all particles to simulate the social behavior of bird flocking or fish schooling.

Velocities and locations can be updated by the following formula,

$$\vec{v}_i(t+1) = w\vec{v}_i(t) + c_1\vec{r}_1 \times (\vec{p}_{best,i}(t) - \vec{x}_i(t)) + c_2\vec{r}_2 \times (\vec{g}_{best}(t) - \vec{x}_i(t)) \quad (4)$$

$$\vec{x}_i(t+1) = \vec{x}_i(t) + \vec{v}_i(t+1) \quad (5)$$

$$w = w_u - (w_u - w_l) \cdot (n_{iter} / n_{\max\_iter}) \quad (6)$$

where $\vec{v}_i(t+1)$ and $\vec{x}_i(t+1)$ are the new velocity and position of particle i at time $t+1$; vector $\vec{v}_i(t)$ and $\vec{x}_i(t)$ represent the original velocity and position of particle i at time t; $\vec{p}_{best,i}(t)$ and $\vec{g}_{best}(t)$ represent the position of the best solution discovered so far by particle i and by all particles in the neighbourhood of particle i; c_1 and c_2 are the acceleration constants; $\vec{r}_1$ and $\vec{r}_2$ are random vectors with a uniform probability from 0 to 1, and w is the inertia weight affecting the velocity of a particle at time t; w_u is the maximum inertia weight and w_l is the minimum inertia weight.

2.3. Embedded System

Embedded system has also been widely used nowadays. It's a simple structure compared to personal computer (PC), which makes it become more popular for some communities. It is expected that the environment will be less complex, with smaller space usage, and low power consumption.

Embedded device used in this research is Portwell product, PQ7-C100XL, with Intel Atom Processor CPU E660. Figure 2 shows the Portwell module. The Intel Atom has low-power, low-cost and high-performance of x86 and x86-64 microprocessors. The package size is 22mm × 22mm, runs at the frequency of 1.3 GHz (2 CPUs) with 512 KB CPU cache. It has 1024 MB RAM. It also has 0.8 – 1.175 Volt core voltages and 3.6 Watt thermal design power [7].

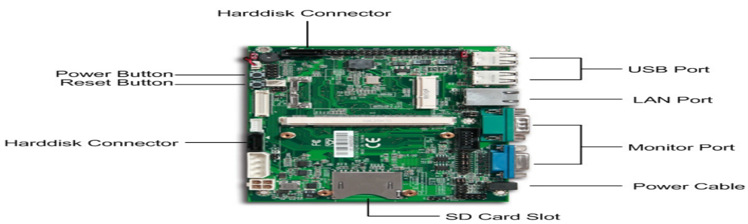


Fig. 2. Embedded device for Portwell PQ7-C100XL

3. Experiments and Results

The NILM system is used to monitor voltage and current waveforms at a single-phase three-wire 110V/220V unbalanced electrical service entrance powering several loads in cases studied. The neural network algorithm in the NILM system identifies three actual loads with steady-state *P* and *Q* signatures. These loads include a 900W vacuum cleaner, a 600W hair dryer, and a 1200W vacuum cleaner.

Table 1 shows that values for the actual test accuracy of load identification in multiple operations are 100% for using features with real and reactive power.

Table 1. The results of load identification in case studies

System Voltage (V)	209	211.2	213.4	215.6	217.8	220	221.2	222.2	226.6	228.8	231
Load 1	1	1	1	1	1	1	1	1	1	1	1
Load 2	2	2	2	2	2	2	2	2	2	2	2
Load 3	3	3	3	3	3	3	3	3	3	3	3
Load 1+2	1+2	1+2	1+2	1+2	1+2	1+2	1+2	1+2	1+2	1+2	1+2
Load 1+3	1+3	1+3	1+3	1+3	1+3	1+3	1+3	1+3	1+3	1+3	1+3
Load 2+3	2+3	2+3	2+3	2+3	2+3	2+3	2+3	2+3	2+3	2+3	2+3
Load 1+2+3	1+2+3	1+2+3	1+2+3	1+2+3	1+2+3	1+2+3	1+2+3	1+2+3	1+2+3	1+2+3	1+2+3

4. Conclusions

To verify the validity of the proposed method, an actual experimental case study is investigated in the paper. Even though the case includes some of the most challenging scenarios for a NILM system to identify such loads with ratings covering a wide spectrum, and simultaneously turn-on/off load, the proposed method yields excellent recognition accuracy for the single-phase three-wire unbalanced distribution system.

Acknowledgement

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract No. NSC 102-2221-E-228-002.

References

[1] Hart GW. Nonintrusive Appliance Load Monitoring. *Proc of IEEE* 1992; **80(12)**: 1870-91.

[2] Hart GW. Residential Energy Monitoring and Computerized Surveillance via Utility Power Flows. *IEEE Technol Soc Mag* 1989; **8(2)**: 12-6.

[3] Laughman C, Lee K, Cox R, Shaw S, Leeb S, Norford L, and Armstrong P. Power Signature Analysis. *IEEE Power Energy Mag* 2003; **1(2)**: 56-63.

[4] Chang HH, Chen KL, Tsai YP, and Lee WJ. A New Measurement Method for Power Signatures of Nonintrusive Demand Monitoring and Load Identification. *IEEE T Ind Appl* 2012; **48(2)**: 764-71.

[5] Chang HH, Lian KL, Su YC, and Lee WJ. Energy Spectrum-Based Wavelet Transform for Non-Intrusive Demand Monitoring and Load Identification. *IEEE Ind Appl Soc Annu Meet (IAS)* 2013: 1-9.

[6] Gurney K. *An Introduction to Neural Network*. Boca Raton: CRC Press; 1997.

[7] PQ7-C100XL User Manual. ver. 1.0. Portwell Inc; 2009.

Biography

Hsueh-Hsien Chang received the B.S. and M.S. degrees in electrical engineering from National Taiwan University of Science and Technology, Taipei, Taiwan, in 1994 and 1996, respectively, and the Ph.D. degree in electrical engineering from Chung Yuan Christian University, Jhongli, Taiwan, in 2009.

From 1996 to 1998, he was a Project and System Engineer with ABB Ltd., Taipei, Taiwan. Since 2013, he has been an Associate Professor in the Department of Electronic Engineering, Jin Wen University of Science and Technology, New Taipei, Taiwan. His current research interests are in neural networks and evolutionary computing applications in power and energy systems, and power quality of power systems.

Putu Wegadiputra Wiratha received the B.S. degree in electrical engineering from Sepuluh Nopember Institute of Science and Technology (ITS), Surabaya, Indonesian, in 2011, and the M.S. degree in electrical engineering from the National Taiwan University of Science and Technology, Taipei, Taiwan, in 2014.

He is currently an engineer in CECI Engineering Consulatants Inc., Taipei, Taiwan. His research interests are energy management and power system engineering.

Nanming Chen graduated from National Taiwan University with BS degree 1973, obtained MS degree from Virginia Polytechnic Institute 1977, and Ph.D. from Purdue University 1980, all in electrical engineering.

Dr. Chen has been a professor of National Taiwan University of Science and Technology (NTUST) since 1989 and a chair professor since 2008. He served as the Dean of Research and Development of NTUST from 2000/12 to 2005/1. He also served as the director of the Advisory Office of the Ministry of Education, Taiwan 2005/09~2008/07, and was also appointed as a director of the Board of Directors, Taiwan Power Company 2004/07~2007/08. His research interest is in power systems, control systems, and railway electromechanical systems. Another administrative specialty is on the vocational and technological education.