NON-INTRUSIVE LOAD MANAGEMENT SYSTEM FOR RESIDENTIAL LOADS USING ARTIFICIAL NEURAL NETWORK BASED ARDUINO MICROCONTROLLER

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I dedicated this thesis to my mother Hajiya Aishatu Ishaq and my father Alhaji Abubakar Ibrahim for their tireless efforts in ensuring my good upbringing through support, guidance and unlimited prayers. May their soul rest in perfect peace and may Allah grant them Jannatul Firdausi. This dedication is also extended to my late wife Asiya Kabir Suyudi, may her soul rest in perfect peace and may she be granted the Jannatul Firdausi by the almighty Allah. My entire family will also be covered in the reward of this work specifically my wife Binta Kabir, my children Asiya Ishaq, Ibrahim Ishaq, Abubakar Ishaq and Ishaq Ishaq. May Allah assists us in giving you a very good upbringing and may all of us be among those that the prophet peace be upon him will be happy with in the day of judgment.

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ABSTRACT

The energy monitoring is one of the most important aspects of energy management. In fact there is a need to monitor the power consumption of a building or premises before planning technical actions to minimize the energy consumption. In traditional load monitoring method, a sensor or a group of sensors attached to every load of interest to monitor the system, which makes the system costly and complex. On the other hand, by Non-Intrusive Load Monitoring (NILM) the aggregated measurement of the building's appliances can be used to identify and/or disaggregate the connected appliances in the building. Therefore, the method provides a simple, reliable and cost effective monitoring since it uses only one set of measuring sensors at the service entry. This thesis aims at finding a solution in the residential electrical energy management through the development of Artificial Neural Network Arduino (ANN-Arduino) NILM system for monitoring and controlling the energy consumption of the home appliances. The major goal of this research work is the development of a simplified ANN-based non-intrusive residential appliances identifier. It is a real-time ANN-Arduino NILM system for residential energy management with its performance evaluation and the calibration of the ZMPT101B voltage sensor module for accurate measurement, by using polynomial regression method. Using the sensor algorithm obtained, an error of 0.9% in the root mean square (rms) measurement of the voltage is obtained using peak-peak measurement method, in comparison to 2.5% when using instantaneous measurement method. Secondly, a residential energy consumption measurement and control system is developed using Arduino microcontroller, which accurately control the home appliances within the threshold power consumption level. The energy consumption measurement prototype has an accurate power and current measurement with error of 3.88% in current measurement when compared with the standard Fluke meter. An ANN-Arduino NILM system is also developed using steady-state signatures, which uses the feedforward ANN to identify the loads when it received the aggregated real power, rms current and power factor from the Arduino. Finally, the ANN-Arduino NILM based appliances' management and control system is developed for keeping track of the appliances and managing their energy usage. The system accurately recognizes all the load combinations and the load controlling works within 2% time error. The overall system resulted into a new home appliances' energy management system based on ANN-Arduino NILM that can be applied into smart electricity system at a reduced cost, reduced complexity and non-intrusively..

ABSTRAK

Pemantauan tenaga adalah salah satu aspek yang paling penting dalam pengurusan tenaga. Malah, terdapat keperluan untuk memantau penggunaan kuasa sebuah bangunan atau premis sebelum merancang tindakan teknikal untuk meminimumkan penggunaan tenaga. Dalam kaedah pemantauan beban tradisional, satu pengesan atau sekumpulan pengesan dipasangkan kepada setiap beban untuk pemantauan sistem, yang menjadikan sistem itu mahal dan kompleks. Sebaliknya, dengan Pemantauan Bebanan Tidak Robos (NILM) pengukuran teragregat peralatan bangunan boleh digunakan untuk mengenal pasti dan/atau mengasingkan peralatan yang bersambung di bangunan. Oleh itu, kaedah ini menyediakan pemantauan yang mudah, boleh dipercayai dan kos efektif kerana hanya menggunakan satu set pengesan pengukur pada kemasukan perkhidmatan. Tesis ini bertujuan mencari penyelesaian dalam pengurusan tenaga elektrik kediaman melalui pembangunan sistem yang tidak robos untuk memantau dan mengawal penggunaan tenaga peralatan rumah. Matlamat utama penyelidikan ini adalah pembangunan pengenal pasti peralatan kediaman berasaskan Rangkaian Neural Tidak Robos dipermudah. Sistem Rangkaian Neural Buatan (ANN)-Arduino (NILM) adalah masa nyata dalam pengurusan tenaga kediaman dengan penilaian prestasi dan penentukuran modul pengesan voltan ZMPT101B untuk pengukuran yang tepat, dengan menggunakan kaedah regresi polinomial. Dengan menggunakan algoritma pengesan yang diperolehi, ralat 0.9% dalam pengukuran voltan punca min kuasa dua (rms) diperolehi menggunakan kaedah pengukuran puncak ke puncak, berbanding 2.5% dengan kaedah pengukuran ketika. Keduanya, sistem pengukuran dan kawalan penggunaan kediaman dibangunkan menggunakan mikropengawal Arduino, yang mengendalikan peralatan rumah secara tepat di dalam tahap penggunaan kuasa ambang. Prototaip pengukuran penggunaan tenaga mempunyai pengukuran kuasa dan arus yang tepat dengan ralat 3.88% dalam pengukuran arus apabila dibandingkan dengan meter piawai Fluke. Sistem ANN-Arduino NILM juga dibangunkan menggunakan signatur keadaan mantap, yang menggunakan ANN suap hadapan untuk mengenalpasti beban apabila menerima kuasa sebenar teragregat, arus rms dan faktor kuasa daripada pada Arduino. Akhir sekali, ANN-Arduino NILM berasaskan sistem pengurusan dan kawalan peralatan dibangunkan untuk mengesan peralatan dan menguruskan penggunaan tenaga mereka. Sistem ini mengenal sepenuhnya dengan tepat semua kombinasi beban dan kawalan kerja beban dalam ralat masa 2%. Sistem keseluruhannya menghasilkan sistem pengurusan tenaga elektrik rumah yang baru berdasarkan ANN-Arduino NILM yang boleh diaplikasikan untuk sistem elektrik pintar dengan kos yang dikurangkan, mengurangkan kerumitan dan tidak robos.

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LIST OF ABBREVIATIONS

AC	-	Alternating Current
ADC	-	Analog to Digital Conversion
ADL	-	Activity of Daily Living
AFAMAP	-	Additional Factorial Approximate MAP
AIA	-	Artificial Immune Algorithm
ANN	-	Artificial Neural Network
BEMS	-	Buildings Energy Management System
CCTV	-	Closed Circuit Television
CFL	-	Compact Fluorescent Lamp
CT	-	Current Transformer
CVD	-	Continuously Varying Devices
CW	-	Current Waveform
DC	-	Direct Current
DENs	-	Distributed Electricity Networks
DMPR	-	Disjoint Multi Path base Routine
DR	-	Demand Response
DWT	-	Discrete Wavelet Transform
ECM	-	Energy Control Manager
EIG	-	Eigen Values
EM	-	Energy Management
EMCUs	-	Energy Management Control Units
EMS	-	Energy Management System
ESD	-	Edge Symbol Detector
EMPT	-	Electromagnetic Transient Program
FHMM	-	Factorial Hidden Markov's Model
FPGA	-	Field Programmable Gate Array
GHG	-	Greenhouse Gas
GMM	-	Gaussian Mixture Model

HAR	-	Harmonics
HEMS	-	Home Energy Management System
HMM	-	Hidden Markov's Model
IAW	-	Instantaneous Admittance Waveform
iHMES	-	In-Home Energy Management System
ILM	-	Intrusive Load Monitoring
IPW	-	Instantaneous Power Waveform
IR	-	Infrared
k-NN	-	k – Nearest Neighbour rule
LED	-	Light Emitting Diode
LDR	-	Light dependent Resistor
MAP	-	Maximum A posteriori Probability
NBC	-	Naïve Bayes Classifier
NILM	-	Non-Intrusive Load Monitoring
OREM	-	Optimization-based Residential Energy Management
PC	-	Personal Computer
PCAT	-	Power Conservation Analysis Tool
PLC	-	Power Line Communication
PSO	-	Particle Swarm Optimization
PT	-	Potential Transformer
rms	-	root mean square
RMSE	-	Root Mean Square Error
ROC	-	Receiver Operating Characteristic
SDM	-	Supply Demand Matching
SoC	-	System on Chip
STFT	-	Short Term Fourier Transform
STW	-	Switching Transient Waveform
SVM	-	Support Vector Machine
TPW	-	Transient Power Waveform
USD	-	United States Dollar
USEPA	-	United State Environmental Protection Agency
WLAN	-	Wireless Area Networks
WMRA	-	Wavelet Multi-Resolution Analysis
ZEM	-	Zigbee Energy Meter

LIST OF SYMBOLS

I	-	Current
I_{ADC}	-	ADC current
I_{ADCref}		Reference ADC current value
I_i	-	Sampled Current
I_{peak}	-	Peak Current
$I_{peak\text{-}peak}$	-	Peak to Peak Current
$Irms$	-	Root Mean Square Voltage
j	-	Order of a Polynomial
$L1$ to $L4$	-	House Appliances
n	-	Total number of samples
P	-	Power
pf	-	Power Factor
S	-	Apparent Power
Q	-	Reactive Power
U_T	-	Total Transient Energy
V	-	Voltage
V_i	-	Sampled Voltage
V_{peak}	-	Peak Voltage
$V_{peak\text{-}peak}$	-	Peak to Peak Voltage
$Vrms$	-	Root Mean Square Voltage
x	-	Independent variable
y	-	Dependent variable
δ	-	Sensitivity of current sensor

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CHAPTER 1

INTRODUCTION

1.1 Background

The usage of electricity at home has since become an essential activity in both rural and urban settings throughout the world. Every now and then the demand of electricity is increasing. New electrical devices and appliances are always emerging at the expense of the users, for they have to be paying the utility companies for operating those devices. However through proper usage, a lot of benefits can be achieved by both the consumers and electrical utility companies [1, 2]. Those benefits, which include energy saving and reduction in greenhouse gas emission will surely come as the results of proper monitoring and management of the power usage.

The appliance load monitoring is the prerequisite activity to every load management, in fact it is through proper monitoring that a management decision can be taken on the connected loads to make the best utilization of the energy. This therefore calls for a system that can monitor the appliances and takes a real time action to manage the energy usage [3-6]. The largest amount of electrical energy sources at global level is from oil and gas sector, which are non-renewable in nature and are estimated to exhausted in the near future. Hence the load monitoring with the view of managing and optimizing the sources is essential in order to reduce the risk of energy crises in the world, by taking energy management actions on the monitored loads. Over the last three decades, the non-intrusive load monitoring has witnessed so many contributions by the researchers in all angles of the research area [7-12]. Some of the works attempted to come out with systems for load controls [13, 14]. Several ways of identifying the connected loads non-intrusively, have existed which include steady-state and transient-state methods of signature extraction [15-17]. Using the steady-state signatures for identifying the home electrical appliances in real time will be more suitable because most of the appliances' operation is in steady-state; therefore a steady-state system can go with the real time load identification of the loads [18]. Previous studies in Non-Intrusive Load Monitoring (NILM) have also indicated the need to use it in energy management of the appliances [2, 19].

The NILM system can be applied in many energy consuming systems to facilitate energy management. For instance, the NILM system can determine the load schedule in an aircraft or motor vehicle from the measurement at the generator level [20-23]. With proper NILM system which is powered by energy consumption data feedback, a very significant saving can be achieved, in fact energy minimization of up to 15% can be achieved from the world wide perspective through changing daily routine of the appliances, low cost stake holding and acquiring more efficient and energy saving electrical appliances [24, 25]. Researchers in the area of energy management pointed out that due to globalization and urbanization of the rural areas, the electricity demand can only be contained by appropriate and efficient energy usage and management [26-28]. Moreover, another analysis found that the residential settings can waste one-third of their energy consumption due to unmonitored operations of various appliances [26].

The home automation through NILM has also been found very useful in helping elderly people to sustain their lifestyle with respect to home daily activities [19]. Also the advances in computer technology, sensor technology and communication facilities will give opportunities for researchers and energy management equipment manufacturers to device many ways of monitoring and managing the load energy consumption [29, 30].

Most of the residential electrical energy management research works are intrusive in nature, which suffers from the weakness of multiple point sensing. The NILM researchers have done a lot in appliances disaggregation and signature extraction, but the NILM systems with real-time energy management capability have not been treated in the research area. The issue of measuring the performance of NILM is another challenging area of NILM, that is why most of the NILM works use distributive metering to check the performance of the systems [2, 31]. This research work focuses on the development of ANN-Arduino based NILM system in order to develop a single point sensing energy management system to replace the existing multiple points sensing systems. The research will also bridge the gap of non-application of the NILM in real-time residential electrical energy management. Moreover, the evaluation of the ANN-NILM in residential appliances control will be a novel method of measuring the performance of NILM,

1.2 Problem Statement

There is need for accurate, simple and cost effective monitoring and management system in all aspects of electrical power consumption. The electrical power consuming system suffers a lot of energy wastage whether at commercial, industrial or residential settings. The residential settings are prominent in energy wastage due to mismanagement, energy unwanted activities and lack of proper load control. The existing researches on home energy management proposed many works on distributed or intrusive load monitoring for home appliances' management [32-34]. However intrusive load monitoring requires sensors or meters at every load of interest, which makes it complex and costly. On the other hand there are many research works regarding the non-intrusive load monitoring which uses one set of measuring devices at the service entry. Though some of these researches are related to the energy management [35-37], but the studies have reputed the need to have an improved real-time NILM for home appliances management at reduced cost and complexity. Various techniques of NILM had been brought up by the researchers that discovered a lot regarding the load identification accuracy, signature extraction and different identification algorithm [38-41], however there is hardly in the literature the use of steady-state NILM technique for residential electrical energy management especially using ANN-Arduino microcontroller based. The use of ANN-Arduino based NILM system for residential energy management will systematically solve the problem of multiple point sensing in ILM and eventually resulted into a cost effective and simple residential energy management using NILM, which will promote the present smart electricity system. The following summarises the problems in the efforts to promote the residential appliances energy management using ANN-Arduino NILM.

- The present residential energy management systems all concentrated on the distributed sensing for controlling the loads. This not only make the system complex and costly, but also affects the reliability of the appliances management as the results of system dependent on multiple sensing. The introduction of single point ANN-Arduino based NILM has vital role to play in ensuring a reliable energy management system.

- Using the steady-state load signatures to identify the appliances will provide more identification accuracy because the steady-state condition is the dominant stage of the load operation [31]. Also the ANN has a great capability of mapping the the load signatures into the load identification even with non-linear relationship between them.

- The Arduino microcontroller takes samples from voltage and current sensors to calculate the steady-state quantities of the appliances consumption. Hence there is need toensure accurate calibration of the sensors, especially the ZMPT101B voltage sensor module which does not have a single sensitivity like the ACS716 current sensor. The calibration of ZMPT101B voltage sensor will provide a universal transfer equation for the sensor.

- There is need to evaluate the ANN-NILM system to see its capability in controlling the home appliances for energy management.

The system can be integrated into smart electricity system to serve as smart home energy monitoring and management system for efficient power consumption. The non-intrusiveness of the NILM system ensures the privacy of the consumers because it can be applied outside the building at meter level.

1.3 Objectives of the Research

The objectives of the research are:

(i) To develop a real-time ANN- Arduino microcontroller based NILM system for home appliances energy consumption management with energy savings capability.

(ii) To develop a simplified ANN-based non-intrusive load identifier for home appliances' identification using steady-state load signatures.

(iii) To develop the voltage sensor algorithm, using polynomial regression analysis for direct and accurate application in the Arduino microcontroller

(iv) To evaluate the performance of the ANN-NILM system in load controlling applications.

1.4 Scopes of the Research

The scope of the research work are bounded as follows:

(i) The research work targeted monitoring and management of residential electrical appliances for energy savings.

(ii) The research work will involve the use of single point measurement, in NILM, to identify the appliances instead of multipoint sensing.

(iii) Steady-state signatures of the loads, which comprises of the real power, rms current and power factor, with acceptable accuracy, are used in the load identification.

(iv) ANN model of the load identifier will be developed using MATLAB.

(v) Arduino microcontroller, current and voltage sensors will be used to develop the system and the ANN model will be implemented in the Arduino.

(vi) The voltage sensor (ZMPT101B module) is calibrated while a factory settings of the current sensor (ACS716) is used.

The ANN-Arduino NILM presented in this research work is limited to some home appliances consisting of Electric bulbs, Standing fans, Electric toaster, Rice cooker, Electric kettle and Blender. Some other appliances like the continuously varying loads are not considered. Also all the experiments are carried out under the standard voltage supply of Malaysia (240V 50Hz), therefore it may have different performance in different voltage supply scenario like 120V or 110V systems.

1.5 Significance of the Research

Non-Intrusive Load Monitoring is a developing research area with ongoing research activities taking place in the area. The application of modern technology in electrical appliance load monitoring and management will revolutionize the energy consumption so that the consumers will make the best use of the power supply. The significance of this research include but not limited to the following:

(i) Improvement in load monitoring, control and load management will make significant improvement and advancement in smart electricity system.

(ii) The sub metering energy monitoring, which involves the monitoring of the appliances in sub groups will benefit immensely from the positive contribution of this research work.

(iii) The research work will provide an alternative way of ascertaining the home appliances operating conditions non-intrusively.

(iv) Researches in load identification using NILM contribute immensely in the load monitoring area, which will subsequently facilitate the best economical and efficient electricity consumption.

(v) The method of residential electrical energy management emanated from this research will be beneficial to the consumers, utility companies, regulatory bodies and all the stakeholders in the nation. As such, the electrical energy monitoring and management is the key factor in conserving the energy resources.

(vi) The ANN-Arduino NILM system also has the advantage that it can be applied outside the building where the appliances are working. This will allow the system to be accessed without disturbing the customer privacy.

1.6 Thesis Organization

The remaining parts of the thesis structure are organized as follows;

Chapter 2 presents an extensive literature review of techniques and methods of NILM which includes signature extraction, disaggregation and identification techniques. It also includes a general literature about ILM techniques and their applications. The chapter also highlights the application of load monitoring in appliances energy management including some of the future research directions.

In Chapter 3 the research methodology is explained, which provides the step by step methods of conducting the research work. It includes the sensor calibration, load monitoring and load controlling systems design.

Chapter 4 provides the results and discussion of the research work. The results of ZMPT101B voltage sensor calibration, the residential energy consumption management using Arduino microcontroller and the results of the non-intrusive load identification based on ANN-Arduino are given in the chapter. It finally presents the results of ANN-NILM evaluation.

The conclusion of the various aspects of the research and recommendations are given in Chapter 5 which also includes the recommendations for future works.

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