ELECTRICITY CONSUMPTION PATTERN DISAGGREGATION BASED ON USER UTILIZATION FACTOR

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To my mother,
my family,
my supervisors,
& my fellow friends,

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ABSTRACT

Non-Intrusive Appliance Load Monitoring (NIALM) technique has been studied intensively by many researchers to estimate the electricity consumption of each appliance in a monitored building. However, the method requires a detailed, second-by-second power consumption data which is commonly not available without the use of high specification energy meter. The common energy meter used in buildings can only capture low frequency data such as kWh for every thirty minutes. This thesis proposes a bottom-up approach for disaggregating kWh consumption of a building. The relationship between the load profile of a building and electricity usage pattern of the occupants were studied and analysed. From the findings, a method based on utilization factor that relates user usage pattern and kWh electricity consumption was proposed to perform load disaggregation. The method was applied on the practical kWh profile data of electricity consumption of Block P19a, Fakulti Kejuruteraan Elektrik, Universiti Teknologi Malaysia. The disaggregated kWh consumption results for air-conditioning and lighting system were validated with the actual kWh consumption recorded at the respective branch circuits of the building. Results from the analysis showed that the proposed method can be used to disaggregate energy consumption of a commercial building into air-conditioning and lighting systems. The proposed method could be extended to disaggregate the energy consumption for different areas of the building.

ABSTRAK

Teknik Pemantauan Perkakas Beban Tidak Bergantung (PPBTB) telah dikaji secara intensif oleh ramai penyelidik untuk menganggarkan penggunaan elektrik setiap perkakas di dalam sesebuah bangunan yang dipantau. Walau bagaimanapun, kaedah ini memerlukan secara terperinci, data penggunaan kuasa setiap saat yang biasanya tidak boleh didapati tanpa menggunakan meter tenaga berspesifikasi tinggi. Meter tenaga yang kebiasaannya digunakan di dalam bangunan hanya boleh merekod data frekuensi rendah contohnya kWh bagi setiap tiga puluh minit. Tesis ini mencadangkan teknik bawah-ke-atas untuk mengasingkan data penggunaan kWh bagi sesebuah bangunan. Hubungan antara profil beban bangunan dan corak penggunaan elektrik oleh penghuni telah dikaji dan dianalisis. Dari hasil kajian, kaedah berdasarkan faktor penggunaan yang menghubungkan corak penggunaan pengguna dan penggunaan elektrik kWh telah dicadangkan untuk melaksanakan pengasingan beban. Kaedah ini diaplikasikan secara praktikal dengan menggunakan profil data kWh di Blok P19a, Fakulti Kejuruteraan Elektrik, Universiti Teknologi Malaysia. Keputusan pengasingan bagi penggunaan kWh untuk sistem penghawa dingin dan pencahayaan telah disahkan dengan penggunaan kWh sebenar yang dicatatkan daripada litar cawangan bangunan masing-masing. Keputusan daripada analisis menunjukkan bahawa kaedah yang dicadangkan boleh digunakan untuk mengasingkan penggunaan tenaga bangunan komersial kepada sistem penghawa dingin dan lampu. Kaedah yang dicadangkan juga boleh digunakan lebih meluas untuk mengasingkan penggunaan tenaga berdasarkan setiap ruang bangunan yang berbeza.

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LIST OF ABBREVIATIONS

AC	-	Air-conditioning system
ANNOT	-	Automated Electricity Data Annotation
APEC	-	Asia-Pacific Economic Cooperation
CU	-	Concordia University
CHP	-	Combine Heat Power
CPU	-	Central Processor Unit
DHW	-	Domestic hot-water
DSM	-	Demand Side Management
DSP	-	Data Signal Processor
EE	-	Energy Efficiency
EMI	-	Electromagnetic Interference
FFT	-	Fast Fourier Transform
FL	-	Lighting system
FKE	-	Fakulti Kejuruteraan Elektrik
FHMM	-	Factorial Hidden Markov Model
FSM	-	Finite State Machines
H	-	High
HELP	-	Heuristic End-Use Load Profiler
HMM	-	Hidden Markov Model
HVAC	-	Heating, ventilation and air-conditioner
IALM	-	Intrusive Appliance Load Monitoring
kHz	-	Kilohertz
kW	-	Kilowatt
kWh	-	Kilowatt-hour

MOHE	-	Ministry of Higher Education's
NIALM	-	Non-Intrusive Appliance Load Monitoring
N-N	-	Neural-network
PE	-	Pencawang Elektrik
PF	-	Power factor
RBF	-	Radial Basis Function
RECAP	-	Recognition of electrical Appliances and Profiling
SMLP	-	Simple Method of formulating Load Profile
SMPS	-	Switch Mode Power Supplies
SVM	-	Support Vector Machines
TOU	-	Time of Use
T5	-	Fluorescent Tube Lamp Type T5
T8	-	Fluorescent Tube Lamp Type T8
UEC	-	Unit Energy Consumption
UK	-	United Kingdom
UNEP	-	United Nations Environment Program
UTM	-	Universiti Teknologi Malaysia
US	-	United States
VH	-	Very high
VL	-	Very low
VRV	-	Variable Refrigerant Volume
W	-	Watt
W/h	-	Watt per hour

LIST OF SYMBOLS

A	-	Utilization factor
i	-	Area
j	-	Time/hour
μ_j	-	mean electricity consumption at hour j
σ	-	Variance
P_i	-	Power input
E_j	-	kWh electricity consumption
N_s	-	Total number of areas
PF	-	Power factor
P_{std}	-	Standard deviation for real power

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Asia-Pacific Economic Cooperation (APEC) Energy Demand and Supply Outlook estimate that electricity demand in Malaysia will significantly rise to 206 TW/h in 2035 from 96.3 TW/h in 2009 [1]. It is said that approximately 30% from the total demand nationwide is contributed by commercial buildings alone [2-4]. Table 1.1 presents regional and sectoral electricity consumption in Malaysia for year 2014. Thus, Malaysia must explore available initiatives to encourage efficient usage of the electricity demand for a better energy management control [5]. University buildings are also one of the high energy consumers and thus, education centres are advised by Ministry of Higher Education's (MOHE) to apply a better energy practice [6-8].

Table 1.1: Regional and sectoral electricity consumption in Malaysia, 2014

REGION	INDUSTRY GWH	COMMERCIAL GWH	RESIDENTIAL GWH	TRANSPORTATION GWH	AGRICULTURE GWH	TOTAL GWH
PENINSULAR MALAYSIA	46,755	37,108	23,721	261	413.5	108,259
SARAWAK	10,966	2,290	1,896	-	-	15,152
SABAH	1,230	2,043	1,647	-	-	4,919
TOTAL	58,951	41,441	27,264	261	414	128,330

There are many strategies to reduce electricity consumption such as demand side management (DSM) and energy efficiency (EE) program. DSM focuses on consumer demand adjustment in energy usage to control energy consumption at end-user through education or financial incentives. EE program is a system to manage and restraining the increase in energy demand. A building that provides same services for less energy input or more services for the same energy input is said to be energy efficient [2, 9]. There are several options to reduce energy consumption waste by providing consumer with their energy level consumption such as smart meter installation known as intrusive appliance load monitoring and analysis of current and voltage waveform through non-intrusive appliance load monitoring method.

Intrusive Appliance Load Monitoring (IALM) is known as one of the most accurate and reliable systems to recognize load consumption of an individual appliance. A few smart meter will be installed to recognized consumers' energy consumption in a building where each meter directly interacts with each involve appliances and finally decomposes the total energy consumption. Apparently, this method is not the common preferred option due to the high cost of installation that requires smart meter to be set up on each appliance.

Meanwhile, the study on Non-Intrusive Appliance Load Monitoring (NIALM) is widely evolving which focuses on load signature behaviour to perform load disaggregation. This method delivers reliable results which conforms with one of the objectives of feedback system that is to achieve appliance disaggregation. A NIALM is designed to monitor an electrical circuit that contains a number of appliances. NIALM estimates the number and nature of the individual loads, their individual energy consumption, and other relevant statistics such as time-of-day variations by a sophisticated analysis of the current and voltage waveforms of the total load. This method is often used to disaggregate overall consumption into individual energy usage of experimented appliances. Besides, the analysis requires less cost than the IALM technique because access to individual components is unnecessary for installing sensors or making measurements.

The study of NIALM is divided into two categories which are low sampling and high sampling installation. Figure 1.1 shows the NIALM method separated into

several divisions, depending on the frequency of input data [10]. Low sampling installation normally analyses the behaviour of power changes and applies macroscopic features due to fundamental period that is 1/60 s or 1/50 s while higher frequency sampling hardware focuses on the study of harmonic and waveforms.

Various studies on NIALM could offer historical usage information to consumers which provide more detail in energy use comparisons and their energy usage per appliance data. Therefore, consumers who are well informed of their current energy usage will be more motivated to change their behaviours toward energy consumption to reduce electricity bill.

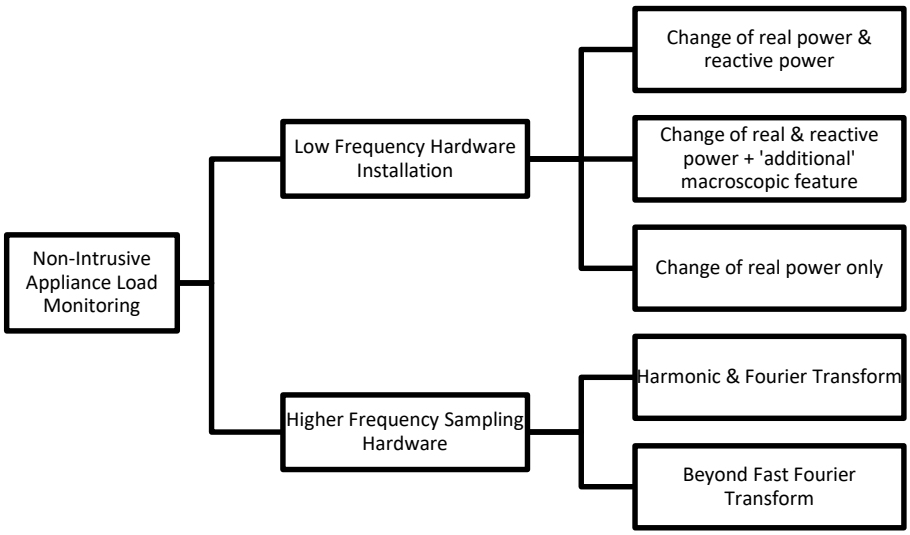

Figure 1.1 Non-Intrusive Appliance Load Monitoring Division [10]

1.2 Problem Statement

Most NIALM method requires high frequency sampling data for load signature tracing before load disaggregation can be made. It also requires a recorder with extensive memory space to store such detail and huge data, which can only be done by

specialized high specification energy meter. In practice, most commercial buildings are only equipped with a standard energy meter, which is only capable in capturing hourly kWh data. Applying NIALM method for such data to disaggregate load is impossible. A load disaggregation method for limited data i.e. low frequency sampling kWh data is needed. The method must able to estimate the usage pattern of major electrical equipment in the building that reflects the electricity usage behaviour of the occupants.

1.3 Objective of the research

The objectives of this research are:

i. To study the relationship between recorded energy consumption (kWh) pattern of a building and the occupant's energy usage behaviour
ii. To propose a load disaggregation method that reflects occupant's energy usage behaviour through bottom-up based utilization factor
iii. To validate the proposed method against actual data

1.4 Scope of the research

This thesis proposes Non-Intrusive Appliance Load Monitoring to disaggregate overall load profile into specific appliance energy usage. Due to the requirement of high specification device and extensive amount of data storage, this study makes use of bottom-up concept to evaluate the relationship between load profile pattern and occupant utilization behaviour. For this purpose, block P19a, Faculty of Electrical Engineering, University Teknologi Malaysia (UTM) is used as a test system for this research. The test system is an academic building which consists of

administration offices, lecturer rooms, class rooms and laboratories. The developed method is tested against practical data of the test system to validate the results. The experimental analysis focuses on estimating the energy usage pattern of two main equipment that influence the high energy consumption of P19a building, which is lighting and air-conditioning system. Other electrical equipment are neglected due to their very low power rating and their presence in total energy consumption is too small compared to lighting and air-conditioning system.

1.5 Significance of the research

Standard energy meter commonly does not provide individual energy data of the equipment installed in a building. Thus, the prospect of estimating energy consumption of various appliance is definitely appealing. Load disaggregation explored in NIALM requires high frequency data and high specification devices. Therefore, a simplified way of load disaggregation method is introduced in this study by correlating the relationship between load profile pattern and occupant utilization behaviour. The proposed method only requires historical data per hour which is accessible through a standard energy meter and simple calculations are involved so that it can be practically applied by the general consumers. The relevance of this study is to offer historical usage information to consumers with more detail energy use comparisons, their energy usage pattern as well as historical data of regular energy consumption. The disaggregated load information provided by the proposed method can inform consumer of their individual appliance energy usage and identifying which appliances are consuming and contribute the most power from their total electricity bills as well as providing guidance for energy-saving behaviours.

1.6 Thesis outline

This thesis is separated into five chapters. Chapter 1 describes the project overview. This chapter consist of background of the research, problem statement, objectives, scope of research and the significance of the research. Chapter 2 presents the literature review that discusses the concept of non-intrusive appliance load monitoring where the idea to disaggregate electrical appliance data consumption is developed. Chapter 2 also reviews the method that was implemented in previous researches that are related to this study. Later in this chapter, the basic idea of bottom-up concept is briefly reviewed. Chapter 3 present the proposed method to be applied in this analysis. It explains the steps taken throughout the proposed method in this study to meet the research objectives. Chapter 4 presents the results and analyses obtain through the proposed method. The result is presented in simple tables, figures and charts as well as detailed clarification of the findings. In this chapter, the extended application of the proposed method is also presented. Chapter 5 is the concluding section of this thesis. The recommendations for future work are also presented in this chapter.

factor and power input of that building needs to be calculated and observed to fit the user behaviour and characteristic of the building.

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