Iranica Journal of Energy and Environment
Journal Homepage: www.ijee.net
IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

Application of IoT and Non-Intrusive Load Monitoring Techniques in Microgrid Energy Management and Monitoring Systems

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PAPER INFO

Paper history:
Received 19 September 2023
Accepted in revised form 17 November 2023

Keywords:
Internet of things
Microgrids
Non-intrusive load monitoring
Smart cities
Smart homes

ABSTRACT

Environmentally sustainable metropolitan environments are characterized by their ability to effectively produce and distribute power while reducing their impact on the environment. Smart homes are essential in smart cities since they enhance sustainability and efficiency in urban settings. A key advantage of smart homes is their capacity to diminish energy use and carbon emissions. This is accomplished by optimizing energy consumption in home appliances, which is customized to fulfill the individual requirements and preferences of consumers. However, there is still a need for further academic research to investigate and improve the functioning of intelligent residential homes in microgrids. To efficiently manage microgrids, it is crucial to gather and analyze large amounts of electrical data related to power production from microgrid sources and energy consumption of the loads. This study examines the use of Non-Intrusive Load Monitoring (NILM) methods to monitor electrical parameters of different loads in microgrids. The research focuses on the application of affordable smart meters that are equipped with Internet of Things (IoT) capabilities. An empirical study showcases the possibility of collecting significant data on microgrid operation via the deployment of an operational microgrid that integrates a hybrid wind-solar power source with a variety of home appliances.

***Doi**: 10.5829/ijee.2024.15.03.07*

INTRODUCTION

Integrating smart homes into microgrids has the capacity to improve the sustainability, efficiency, and resilience of urban areas. In addition, during times of reduced demand, it becomes possible to redirect the surplus energy generated into the power grid (1). The concept of smart cities has undergone a transformation, progressing towards increasingly intricate ecosystems (2-4). These systems are distinguished by the extensive utilization of smart technology, the incorporation of renewable energy sources and energy conservation systems, and the advancement of intelligent transportation systems (5). Moreover, these entities are additionally distinguished by the advancement of ever intricate data analysis techniques and the ongoing expansion of the Internet of Things (6).

A microgrid can be characterized as a small-scale electrical grid that has the capability to function autonomously or in conjunction with the larger power grid by utilizing local generation sources, such as renewable energy systems, and energy storage technologies (7). Considering the fact that urban areas are significant contributors to the production of greenhouse gases, it is possible to mitigate these adverse impacts by incorporating renewable energy sources into the electrical generation systems of cities. One of the primary advantages associated with the use of microgrids in smart cities pertains to the enhancement of energy reliability and resiliency (8). Microgrids have the capacity to generate and distribute electricity at a localized level, hence enabling the provision of electric power to essential infrastructure and services in the event of grid disruptions or natural calamities (9). One further benefit of microgrids is in their capacity to incorporate renewable energy sources into the overall energy composition. Furthermore, microgrids possess the capability to mitigate energy expenses through the optimization of energy consumption and the alleviation of peak demand on the primary power grid (10). This phenomenon has the potential to generate cost savings for both consumers and

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Please cite this article as: Esmaeili Shayan M. Application of IoT and non-intrusive load monitoring techniques in microgrid energy management and monitoring systems, Iranica Journal of Energy and Environment, 2024 July, 15(3): 287-93. Doi: 10.5829/ijee.2024.15.03.07

utilities, while also alleviating the burden on the broader power system during moments of high demand (11).

Smart homes are considered a crucial component of sustainable smart cities(۱۲) . Smart homes are comprised of residences that are outfitted with intelligent equipment and appliances capable of intercommunication with each other and the electrical grid (13). This integration empowers consumers to exercise greater authority over their energy consumption and associated expenses. The integration of smart houses inside microgrids can be achieved through many mechanisms (14), so facilitating the optimization of energy consumption and the enhancement of energy efficiency. The integration of smart houses inside microgrids enables homeowners to produce electricity from renewable energy sources and utilize it for powering household appliances. Any surplus electricity can be stored in batteries or returned to the main power grid (15). This enables individuals to decrease their dependence on the centralized power grid and maybe achieve cost savings on their energy expenditures. The implementation of smart meters and energy management systems can facilitate the effective administration of data within microgrids (16).

Furthermore, the use of microgrids enables smart homes to actively engage in demand response initiatives, wherein homeowners have the ability to curtail their energy consumption during instances of heightened grid demand (9, 17). This practice aids in alleviating stress on the electrical grid and has the potential to provide households with incentives or credits for their active involvement. The measurement of energy consumption of household appliances is a crucial aspect for smart homes situated within microgrids, as it enables the implementation of intelligent control systems that can effectively reduce energy usage. In addition, the assurance of cyber-security can be achieved by the implementation of secure measurement, communication, and control protocols (18, 19).

Several studies have suggested various smart metering infrastructures that can be implemented in microgrids (19). Smart meters are sophisticated devices capable of monitoring and measuring various energy metrics of diverse loads, encompassing household appliances (20). The proposed methodology for monitoring and analyzing energy variables in a microgrid is structured into distinct stages.

- The initial task involves identifying the quantity and classification of smart meters that will be deployed within the microgrid. One potential technique is the implementation of Intrusive Load Monitoring (ILM), as suggested by Gao, et al. (21). This method involves the utilization of low-cost electricity meter devices that directly measure the energy consumption of individual devices. In this approach, smart plugs or other similar devices establish communication with the smart meter to provide real-time information regarding energy usage. Given the potentially enormous number of loads, the utilization of numerous smart meters may prove to be cost-prohibitive (22). Non-Intrusive Load Monitoring (NILM) approaches can be employed as an alternative in light of this rationale (23, 24). In practical applications, the latter option frequently involves the utilization of a singular meter for quantifying power generation, while employing another meter to assess the aggregate demand across various appliances. The utilization of affordable smart meters with great precision, such as the openZmeter device (25), can be justified for this purpose. The efficacy of this intelligent meter in accurately measuring electrical data pertaining to household appliances has been demonstrated (26). Consequently, due to its affordability, compact dimensions, and straightforward installation process, it can be readily implemented in multiple locations within the microgrid. This facilitates the observation of power transfers between the microgrid and the primary grid, as well as between the distributed generation and batteries, at a granular level encompassing individual devices.
- The implementation of smart meters: The proposal suggests employing a limited number of openZmeter devices for the purpose of monitoring power generation and energy consumption within the microgrid. Figure 1 illustrates the mechanism by which openZmeter collects energy data from household appliances at a singular location, thereafter transmitting this data to a computer responsible for processing the acquired information. Homeowners have the option to utilize either a website or a mobile application to access and monitor their energy consumption data, as well as get notifications in the event of any anomalous readings detected by the smart meter.

Data processing involves the utilization of real-time energy usage data by homeowners to enhance energy efficiency through various means such as modifying device settings, deactivating idle equipment, or upgrading

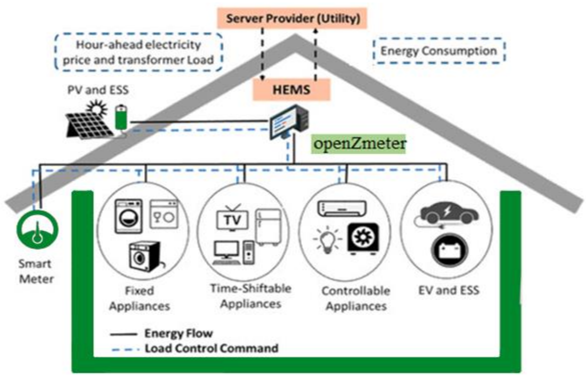

Figure 1. The openZmeter is utilized for the measurement of energy characteristics in domestic appliances

to more energy-efficient models. In order to achieve this objective, the utilization of artificial intelligence techniques can be employed (27).

As previously mentioned, this measurement technique facilitates the utilization of non-intrusive load monitoring (NILM) approaches (28). A significant field of research pertaining to Non-Intrusive Load Monitoring (NILM) encompasses the examination of methodologies that specifically aim to separate the overall power consumption of a residential or commercial structure into data pertaining to the power consumption of individual appliances (29). This data can be utilized to detect appliances that consume high levels of energy and enhance their energy efficiency, resulting in energy conservation and decreased electricity expenses. The ideas of smart cities, microgrids, and smart homes are interrelated in the context of promoting sustainable urban development. A smart city is a city that incorporates advanced technology and data-driven solutions to improve the quality of life for its citizens and support sustainable growth in urban areas (30). One potential strategy for a smart city to accomplish this objective is through the integration of microgrids, which are self-sustaining energy systems capable of functioning autonomously from the primary power grid. Smart homes refer to residential structures that utilize contemporary technology and automation systems with the aim of enhancing energy efficiency and waste management (31).

This study presents a comprehensive examination of the monitoring and analysis of energy and power quality characteristics within microgrids that incorporate home devices, utilizing modern smart meters. In pursuit of this objective, Section 1 provides a comprehensive examination of contemporary developments pertaining to smart cities and microgrids, as well as the use of sophisticated power metering techniques within these contexts. Section 2 of this research paper outlines the materials and methods employed in the inquiry, and provides a detailed account of a case study conducted in an authentic setting. Section 3 of this study ultimately provides the primary findings and outlines potential avenues for future research.

MATERIAL AND METHODS

The case study was conducted within the microgrid situated in Tehran, Iran, at the geographic coordinates of 35.7219° N and 51.3347° E, as depicted in Figure 2. The generation system comprises two solar tracker systems, each with a capacity of 3600 watts, employed for the purpose of harnessing solar energy to produce electricity. Additionally, it is possible to integrate three wind turbines into the microgrid system. The energy that is produced is subsequently stored in batteries to be used later during periods of reduced energy output or increased energy demand. The batteries inside the microgrid are tasked with the responsibility of effectively managing and storing the energy produced by the renewable sources, thereby guaranteeing a consistent and uninterrupted provision of electricity to the various loads. The microgrid encompasses a diverse range of loads, comprising numerous household equipment such as refrigerators, air conditioners, and lighting fixtures, among other examples. These gadgets utilize energy from both conventional batteries and renewable sources, taking advantage of the latter when they are accessible. The controller is responsible for the regulation of battery charging and discharging processes, the allocation of energy to various loads, and the seamless transition between different renewable energy sources based on their respective availability.

RESULTS AND DISCUSSION

The openZmeter device possesses the capability to collect instantaneous data pertaining to the primary electrical parameters. For instance, the measurement of energy production is of utmost significance in assessing the adequacy of electricity generation inside the microgrid to satisfy the prevailing demand. The power generated by the solar panels over the course of a week is depicted in Figure 3. It is evident from the graph that the sun intensity exhibits periodic variations, as seen by the repeated patterns.

Conversely, the openZmeter device is employed for the purpose of quantifying the electrical parameters associated with the loads within the microgrid. Figure 4 illustrates the energy consumption patterns of various appliances within a 2-hour timeframe. The data reveals notable disparities in energy usage among different appliances, with the television, fridge, and kitchen hood

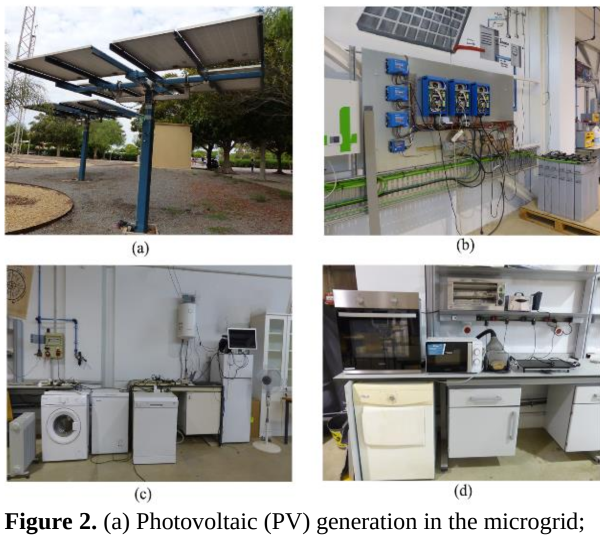

Figure 2. (a) Photovoltaic (PV) generation in the microgrid; (b) Power electronics and batteries; (c) and (d) domestic appliances (loads)

Figure 3. Microgrid energy produced from renewable sources

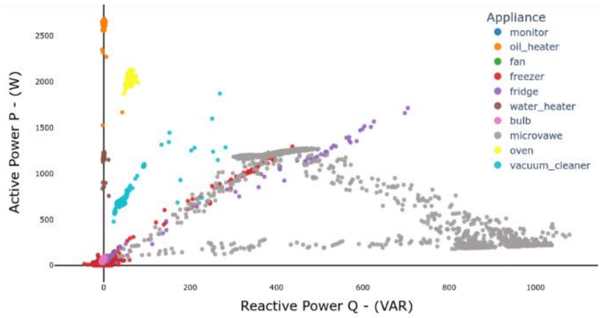

Figure 5. Home appliances' active and reactive power

Figure 4. Microgrid energy usage

exhibiting relatively modest energy consumption, while the oven and water heater demonstrate much higher levels of energy consumption.

In addition to assessing active power, it is crucial to additionally quantify reactive power (32). Active or real power, denoted in watts (W), refers to the electrical power that is utilized by a device and transformed into practical output, such as generating heat, light, or motion.

Conversely, reactive power, quantified in volt-amperes-reactive (VAR), is the segment of electrical power that does not contribute to productive tasks, but rather is necessary for certain devices (such as motors, transformers, and fluorescent lamps) to generate and sustain magnetic fields. Figure 5 illustrates the active and reactive power consumption of various household appliances as measured by the openZmeter. Each data point in the figure corresponds to a measurement recorded at a frequency of 200 milliseconds. The evidence demonstrates that heating element loads, such as ovens and bulbs, exhibit a predominantly resistive nature. Consequently, these appliances consume a minimal quantity of volt-ampere reactive (VAR) power.

In contrast, other appliances like vacuum cleaners, microwaves, and freezers consume more significant quantities of reactive power.

Additionally, the openZmeter possesses the capability to acquire power quality data that holds significant value inside the microgrid context. In a more particular manner, openZmeter records the occurrences in accordance with the EN50160 power quality standard (33). As depicted in Figure 6, the microgrid exhibits frequency fluctuations in relation to the standard 50 Hz frequency, which is often employed in electrical networks across Iran and numerous other regions globally. OpenZmeter is capable of measuring additional power quality characteristics, such as harmonics and the flicker effect.

It is evident that not all power quality factors achieved a visually distinct separation. The clusters are dispersed over the search space and do not form distinct entities. This phenomenon may arise due to the fluctuating

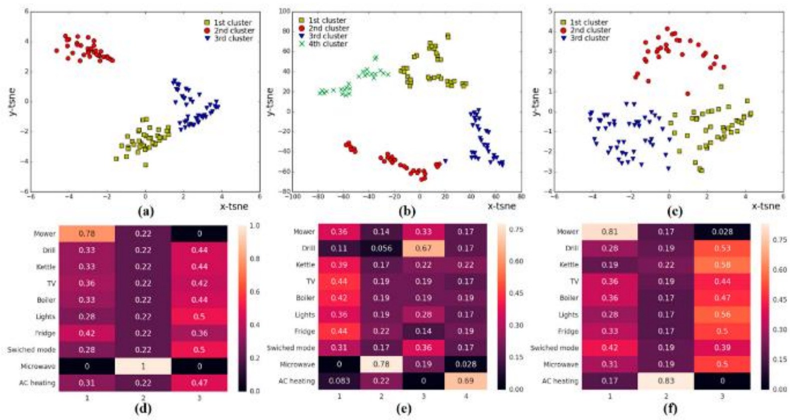

Figure 6. Home appliances' active and reactive power

influence of the appliances on the network or the network's adaptation. Consequently, the power quality responses do not exhibit a notable magnitude. The clustering of PQ parameters is advancing at a 100% state of completion. The calculated probabilities of appliances being assigned to specific clusters are as follows: (a, d) represents voltage frequency with corresponding appliance probabilities, (b, e) represents total harmonic distortion of voltage with corresponding appliance probabilities, and (c, f) represents V with corresponding appliance probabilities. Nevertheless, some appliances, particularly the microwave, drill, mower, and air conditioner heating, may be accurately distinguished, indicating that their existence influences the system to exhibit a certain behavior in relation to a specific power quality parameter.

In additional research, there is a planned endeavor to explore the incorporation of high-dimensional data through the utilization of machine learning and prediction methodologies (34, 35). The objective of this study is to examine the utilization of various methodologies, such as soft computing techniques (36, 37), in order to enhance the optimization of energy management inside microgrids.

CONCLUSION

Evaluating energy and power quality indicators in a microgrid that feeds electricity to a smart home is crucial for assuring the efficiency and reliability of the energy supply needed to support smart cities. Smart meters play a crucial role in gathering up-to-date information on energy use, generation, and power quality measurements, such as voltage, current, power factor, and harmonics. This paper presents an overview of the methodology employed for monitoring energy data through the utilization of a collection of affordable smart meters equipped with IoT capabilities. The objective is to gather measurements from a microgrid encompassing a hybrid wind-solar generation system, a battery, and a selection of household appliances. The findings indicate that information can be collected from different components of the microgrid in order to support the optimization of energy utilization. Smart meters have the capacity to offer significant insights into the quantification of energy generation and consumption. This data can be utilized by homeowners and utility providers to enhance energy management, minimize inefficiencies, and improve energy generation to align with the prevailing demand. Conversely, smart meters possess the capability to measure power quality metrics in real-time, thereby offering valuable insights into the overall quality of the electrical supply. The provided data can be utilized for the purpose of identifying and resolving power quality concerns that may result in appliance damage or energy inefficiency. Additionally, it serves to guarantee the dependability and robustness of the microgrid system. Furthermore, with precise monitoring of energy usage, operators of microgrids have the ability to uncover potential avenues for diminishing energy consumption, optimizing energy production, mitigating energy expenses, and curbing carbon emissions. This optimization is achieved by effectively utilizing information obtained from power sources, storage systems, and energy-consuming appliances. The topic of interest pertains to the active and reactive power consumption of household appliances.

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Persian Abstract

چکیده

کشورهایی با الگوی توسعه پایدار به دلیل توانایی تولید و توزیع مؤثر انرژی و کاهش تأثیرات زیست محیطی متمایز می‌شوند. ساختمان‌ها به عنوان بخش تعیین کننده در مصرف انرژی در شهرهای هوشمند در تحقق پایداری و کارآمدی موثر هستند. یکی از مزایای کلیدی خانه‌های هوشمند قابلیت کاهش مصرف انرژی و انتشار گازهای کربنی است. این امر با بهینه‌سازی مصرف انرژی در لوازم خانگی با توجه به ترجیحات فردی مشتریان انجام می‌شود. با این حال، هنوز نیاز به تحقیقات عمیقتر برای بررسی و بهبود عملکرد خانه‌های هوشمند در ریز شبکه‌ها وجود دارد. در این تحقیق قابلیت اینترنت اشیاء (IoT) و مطالعه تجربی اندازه‌گیری هوشمند مبتنی بر هزینه معرفی شده و مدیریت کارآمد ریز شبکه‌ها، جمع‌آوری و تجزیه و تحلیل حجم زیادی از داده‌های الکتریکی تجهیزات بررسی می گردد. استفاده از روش‌های نظارت بر بار غیر نفوذی (NILM) برای نظارت بر پارامترهای الکتریکی بارهای مختلف در ریز شبکه‌ها از نوآوری‌های تحقیق می‌باشد. این سامانه از طریق استقرار یک ریزشبکه عملیاتی که منبع تولید ترکیبی باد-خورشیدی و مجموعه‌ای از لوازم خانگی را به صورت یکپارچه بررسی و مصرف انرژی هر بخش را نمایش می‌دهد.