Rev.int.med.cienc.act.fís.deporte - vol. 24 - número 97 - ISSN: 1577-0354

Binghui Z et al. (2024) OPTIMIZING ENERGY MANAGEMENT IN SPORTS FACILITIES: HARMONIC ASSESSMENT AND MULTI-LOAD TRACKING MECHANISMS FOR ENHANCED PERFORMANCE. Revista Internacional de Medicina y Ciencias de la Actividad Física y el Deporte vol. 24 (97) pp. 341-362.
DOI: https://doi.org/10.15366/rimcafd2024.97.024

ORIGINAL

OPTIMIZING ENERGY MANAGEMENT IN SPORTS FACILITIES: HARMONIC ASSESSMENT AND MULTI-LOAD TRACKING MECHANISMS FOR ENHANCED PERFORMANCE

Dang Sanlei[1], Yao Zhicong[1], Zhang Yongwang[1], Zhao Binghui[1*], Zhao Wen[1]

[1] Measurement Center of Guangdong Power Grid Co., Ltd; Qingyuan Guangdong 511543 China.
E-mail: binghui0921@163.com

Recibido 24 de diciembre de 2023 **Received** December 24, 2023
Aceptado 24 de julio de 2024 **Accepted** July 24, 2024

ABSTRACT

Energy meters, traditionally used in residential, commercial, and industrial settings to measure and record electrical energy usage, play a critical role in billing and energy management. In the realm of sports, where facilities often encompass a variety of high-energy-consuming activities ranging from lighting vast stadiums to powering high-intensity training equipment, efficient energy management becomes crucial for both operational sustainability and financial viability. This study explores the adoption of a smart energy meter equipped with Internet of Things (IoT) technology, specifically tailored for the unique energy demands of sports facilities. The advanced smart energy meter utilizes an Improved Fast Fourier Transform (IFFT) to manage and monitor energy usage more effectively in sports environments. This approach includes Total Harmonic Distortion (THD) Computing and Root Mean Square Voltage (RMSV) Measurement, which are critical for accurately determining Vrms and THD values. Such precise measurements are essential for sports facilities to prevent energy waste and ensure the reliability of critical systems like field lighting and climate controls, which directly affect athletic performance and spectator experience. Furthermore, the integration of the Hanning Window (HW) method reduces spectrum leakage, enhancing the reliability of harmonic analysis. This is particularly important in sports complexes where sudden changes in energy use—such as those occurring during major events or games—can lead to significant fluctuations. Reliable harmonic analysis helps in maintaining consistent power quality, protecting sensitive training equipment from potential damage caused by power irregularities. Using Node-RED, a cloud-based platform, the smart energy meter facilitates the secure collection, management, and transfer of energy data, enabling sports facility managers to perform real-time monitoring and make informed decisions regarding energy use. A comparative analysis against traditional Discrete Fourier Transform (DFT) and Fast Fourier Transform (FFT) methods highlights the superiority of the IFFT approach in sports settings, demonstrating its enhanced capabilities in power quality management and operational efficiency. In conclusion, the implementation of smart energy meter technology in sports facilities not only enhances energy efficiency and reduces costs but also plays a crucial role in optimizing the performance and sustainability of sports operations. This technology supports the broader goals of environmental stewardship and economic management in the sports industry, ensuring that facilities can meet the high standards required for both competition and training.

KEYWORDS: Energy meter; Internet of Things (IoT); Improved Fast Fourier Transform (IFFT); Root Mean Square Voltage Measurement (RMSV); Hanning Window (HW)

1. INTRODUCTION

The integration of advanced technology in sports facility management has become indispensable in an era focused on sustainability and efficiency. Sports complexes and arenas, which are energy-intensive environments due to their extensive use of lighting, HVAC systems, and digital equipment, stand to benefit significantly from the implementation of smart energy meters. These devices not only streamline energy consumption but also enhance the operational efficiency and environmental footprint of sports venues (Mahapatra & Nayyar, 2022; McWilliams, Weinreb, Ding, Ndumele, & Wallace, 2023; Parvin et al., 2022; Veskioja, Soe, & Kisel, 2022). Energy efficiency in sports facilities is not merely a matter of reducing costs but also of enhancing the performance environment and ensuring the comfort and safety of athletes and spectators. For example, precise control over lighting and temperature is crucial in sports like gymnastics or ice hockey, where environmental conditions directly affect athletes’ performance and safety. Smart energy meters enable such precision by providing real-time data and automated control systems that adjust settings based on current needs and occupancy, significantly reducing energy waste. From an economic perspective, sports facilities are under increasing pressure to reduce operational costs and demonstrate sustainability (Albatayneh, Juaidi, Abdallah, Pena-Fernandez, & Manzano-Agugliaro, 2022; Kumar, Alghamdi, Mehbodniya, Webber, & Shavkatovich, 2022; Rezaeimozafar, Monaghan, Barrett, & Duffy, 2022). Energy costs constitute a large portion of the operational expenses in these facilities. Implementing smart energy solutions can lead to substantial cost savings. For instance, a study by the Environmental Protection

Agency (EPA) suggested that commercial buildings, including sports facilities, can reduce their energy use by 10 to 30% through the implementation of smart technologies and energy-efficient practices. Smart energy meters utilize cutting-edge technologies such as the Internet of Things (IoT), cloud computing, and advanced algorithms for energy management. These meters can track usage patterns across various loads, identify inefficiencies, and suggest or automate adjustments to optimize energy use (Ahammed & Khan, 2022; Akkad, Wills, & Rezazadeh, 2023; Chaudhuri, Datta, Kumar, Davim, & Pramanik, 2022; Jabbar, Annathurai, Rahim, & Fauzi, 2022). Techniques like the Improved Fast Fourier Transform (IFFT) are employed to enhance the accuracy of real-time monitoring, while algorithms capable of calculating Total Harmonic Distortion (THD) and Root Mean Square Voltage (RMSV) ensure that the power quality is maintained at levels that prevent damage to sensitive electronic equipment and reduce the risk of outages. While the benefits are clear, the adoption of smart meters in sports facilities also presents challenges (Buonomano, Barone, & Forzano, 2022; Meeks, Omuraliev, Isaev, & Wang, 2023). These include the initial investment costs, the need for staff training on new systems, and the integration of these systems into older facilities that were not originally designed with such technology in mind. Despite these challenges, the long-term benefits—improved energy management, enhanced athlete performance, and greater spectator satisfaction—justify the initial outlay. This study aims to provide a comprehensive analysis of how smart energy meters' impact energy management in sports facilities, with a particular focus on the resulting economic benefits, sustainability improvements, and enhancements in athletic performance environments. The broader implications of this research could influence policy decisions, encourage the adoption of similar technologies in other high-energy-use industries, and contribute to broader environmental goals such as reduced greenhouse gas emissions.

2. Literature Review

The study (Li, Shi, Shinde, Ye, & Song, 2019) introduced an approach for energy evaluations and analytics-driven IoT management. The researchers utilized the energy meter values to construct a dual deep learning (DL) model system. The system was designed to learn and understand the behaviors of the system under normal operating conditions. The implementation of an innovative architecture enables the detection of both cyber and physical threats. The disaggregation approach was utilized to examine the usage patterns of individual subsections inside a system to determine potential cyberattacks. The aggregation approach was employed to find physical attacks by comparing the actual energy usage with the expected outcomes and characterizing any variations. Based on energy usage statistics, the suggested system detected instances of cyber and physical attacks. The researchers (Pawar & TarunKumar, 2020) suggested the implementation of "Intelligent Smart Energy Management Systems (ISEMS)" as an approach for managing energy demand in a smart grid context characterized by a significant presence of renewable energy sources. The suggested technique involved the evaluation of multiple predictive techniques to achieve precise energy projections, encompassing both hour and day-ahead scheduling. The “Particle Swarm Optimization (PSO) based Support Vector Machine (SVM) regression framework” has showed superior performance accuracy compared to other predictions models. Subsequently, the ISEMS experiment set-up was executed using various setups, taking into consideration user convenience and essential features, in accordance with the projected information. Furthermore, the integration of the IoT ecosystem has been established to facilitate user-end management. The study (Abate, Carratù, Liguori, & Paciello, 2019) investigated the methods employed for energy assessments and transmission. The researchers presented up a cost-effective intelligent electric meter architecture for the purpose of measuring electrical properties. The meter demonstrated the capability to adjust the variations in the grid, so ensuring a consistent and precise amount of measurement accuracy. Two approaches have been established and contrasted on the suggested smart meter, using simulated and experimental signals. A “distributed block chain access management system for Internet of Things smart grids (DBACP-IoTSG)” was developed by the researchers of (Bera, Saha, Das, & Vasilakos, 2020). Data from individual smart meters (SMs) was transmitted to service providers in an efficient and secure way using the DBACP-IoTSG that was suggested.

The P2P network was established by the collaborating service providers, with the peer nodes producing blocks using data collected from their SMs. Since the information gathered from SMs' users is confidential and sensitive, the block chain was assessed as reliable. A detailed analysis demonstrated that DBACP-IoTSGenabled numerous additional characteristics and established more protection in addition to the accessible combination and computational expenses. The study (Mudaliar & Sivakumar, 2020) focused on the implementation of an IoT based system for real-time energy surveillance in the switchgear industries. The Raspberry Pi has been considered for its affordability and robust innovation to monitor industrial energy usage. The Raspberry Pi was employed in conjunction with the Node.js software program to gather data pertaining to various electrical characteristics from the pre-existing energy meters inside an industrial environment. The data was stored, allowing for convenient access through laptops or mobile phones with the utilization of Grafana. The monitoring framework demonstrated to be beneficial for the sector in comprehending the daily energy patterns, a crucial aspect in implementing conservation initiatives with the objective of reducing energy usage. Researchers of (Yang & Wang, 2021) established a “transactive energy management (TEM) mechanism for IoT-enabled smart homes” that was based on the block chain. They considered about all the different ways that smart houses could get engaged in the trans active energy economy. The traditional TEM approach has issues like low efficiency, privacy leakage, and a single point of failure. To overcome those obstacles, they created a distributed algorithm that protect user confidentiality while allowing them to regulate their consumption of energy through a block chain-based smart contract. Also, the smart contract for the overall TEM mechanism was constructed and a block chain system optimized for IoT devices was implemented.

The findings demonstrated that the block chain-based TEM mechanism could be implemented on real-world IoT devices while reducing the total expense. The selection of the most suitable Cluster Head (CH) was investigated in the study (Iwendi et al., 2021) to optimize the usage of energy inside the IoT network. The study utilized a hybrid metaheuristic method, specifically the “Whale Optimization method (WOA) in conjunction with Simulated Annealing (SA).” In order to determine the most suitable CH inside the IoT network, many performance indicators have been employed. Those metrics included the number of active nodes, load distribution, temperature, and cost functions. The suggested method was evaluated against various cutting-edge optimization methods, including the “Artificial Bee Colony algorithm, Genetic Algorithm, Adaptive Gravitational Search algorithm, and WOA.” The findings demonstrated the superior performance of the suggested hybrid technique in comparison with traditional approaches. The construction of intelligent irrigation systems capable of covering expansive urban regions was described by the authors of (Froiz-Míguez et al., 2020). That was achieved through the implementation of sensor nodes that utilized “Low-Power Wide-Area Network (LPWAN)” technology, specifically LoRa and LoRaWAN. The IoT nodes were employed to gather data on soil temperature, soil moisture, and air temperature. Additionally, those nodes were responsible for regulating the water supply. The data align with simulation findings, demonstrated the influence of shadowing impacts and substance properties on the electromagnetic transmission of near-ground and underground LoRaWAN communications. The findings obtained from the study offered valuable insights to potential manufacturers of smart irrigation systems. Authors of (Barman, Yadav, Kumar, & Gope, 2018) recommended the development of a smart energy meter utilizing the IoT technology. The “smart energy meter, which utilized the ESP 8266 12E Wi-Fi module”, was designed to regulate and compute usage of energy. The meter transmitted the data to the cloud, allowing consumers or producers to access and evaluate the readings.

Therefore, energy evaluation by the user became much more simple and regulated. Furthermore, the technology performed a crucial role in identifying instances of power stealing. The implementation of smart meters facilitated home automation through the IoT, hence enabling wireless communication. The development can be considered a significant advancement towards the realization of the Digital India initiative. The study (Elsisi, Mahmoud, Lehtonen, & Darwish, 2021) presented an architecture that utilized ML techniques for the purpose of analyzing and monitoring the output data generated by smart meters.

The primary objective of the architecture was to determine the authenticity of the data, identifying between authentic and duplicates information. The presence of fake data can be attributed to the occurrence of hacking incidents and the inefficiency of the meters. The efficiency of the meters was influenced by many factors present in a manufacturing facilities. In addition, the suggested architecture has been verified to assess the extent of data loss occurring across communication channels. The DT algorithm was employed as a proficient machine learning technique to do both classification and regression analyses on the data from the meters. The suggested architecture outcomes provided a dependable and efficient industrial solution that promotes investments in Industry 4.0. Authors of (S. Jain, Pradish, Paventhan, Saravanan, & Das, 2018) examined the implementation of smart metering in India, considering both rural and urban contexts. They determined that the built-in short-range IoT solution may not always meet the long-range requirements well. Additionally, the authors emphasized the potential of LPWAN methodologies for facilitating the development of a dependable, cost-effective, energy-efficient, long-distance communication solution for smart energy metering applications. The researchers highlighted the prototype utilization of end-to-end LoRa communications for a metering system and discussed on the ultimate visual framework. The study (Saleem et al., 2023) presented a smart energy management system designed for smart settings. The framework integrated an “Energy Controller and an IoT middleware” to facilitate effective demand-side control. The Energy Controller received data on energy use from every device that was connected to it, each of which was outfitted with IoT sensors and actuators. The system was designed to enhance the efficiency of air conditioning operations by considering temperature variations and the characteristics of the building.

The technique showed superior performance compared to conventional controllers through the utilization of real-time monitoring and advanced algorithms. The findings of the study revealed a range of energy reductions from 15% to 49%, so emphasizing the potential for cost reduction, positive environmental impacts, and increased equipment lifespan as an outcome of implementing continuous monitoring and enhanced air conditioning control. Researchers of (Karpagam, Sahana, Sivadharini, & Soundhariyasri, 2023) developed a smart energy meter based on the IoT for the purpose of detecting power theft. The model under consideration comprised of components such as “Arduino UNO, ESP8266, AC713 current sensors, and other relevant elements.” The AC713 device detected current consumption by utilizing the ESP32 microcontroller, which transmitted the data to the IoT platform. Although AMR (Automatic Meter Reading) proved to be a highly effective technique, it incurred significant expenses for the proxy of existing energy meters by SEM, which showed a high level of inefficiency. Consequently, the method under consideration prioritized the identification of power theft instances resulting from unauthorized interference by members of the public. The model under consideration was implemented through the utilization of BLYNK software and simulated utilizing PROTEUS technology. The validity of the suggested strategy was assessed through the utilization of simulated outcomes. The study (Rostampour et al., 2023) presented a novel approach for enhancing communication security and protecting user confidentiality in smart grid applications through the implementation of a mutual authentication and key agreement mechanism. The "Enhanced Authentication Process to Secure Smart Grid Infrastructures (EPSG) method utilized both an Elliptic Curve Cryptography (ECC) module and a Physical Unclonable Function (PUF)" concurrently to achieve sufficient amounts of security and stability. The security evaluation has provided that the EPSG exhibited a strong security posture in relation to both message transfers on the communication channel and physical attacks. Furthermore, the EPSG showed resistance against modeling attacks, which was considered one of the primary vulnerabilities associated with PUF modules. In addition, the efficiency of the proposed EPSG was demonstrated through a comparison effectiveness assessment using an Arduino UNO microcontroller. The evaluation assesses computational complexity, communication costs, and energy usage. An IoT based energy meter monitoring mechanism with error reporting was proposed by the authors of (R. Jain, Gupta, Mahajan, & Chauhan, 2019). Specify mode and get notified by text message. There was a switch to choose between modes. The appliances were programmed into an automatic mode that would turn them off when the power went off to save money. The electronic meter would alert the customer in the event of a malfunction.

The E-meter's LED would light up if there were a problem. Data can be stored in flash memory using "EEPROM (Electrically Erasable Programmable Read Only Memory)." The project's benefits included spending less money, using less energy, and spending less time on it. ARUDINO IDE (with embedded C language) was utilized for both the software and the hardware components of their search. The research (Singh & Yassine, 2019) presented a comprehensive framework that facilitated novel functionalities for the efficient analysis of high-resolution energy usage data in close to real-time. The authors provided forward a proposal for an IoT big data analytics infrastructure that utilized fog computing in order to manage the complicated problems and resource requirements associated with near live information processing, storage, and classification evaluation. The article presented a depiction of the design structure and needs of the suggested architecture, along with the validation of the analytics elements using datasets obtained from actual residential properties. Author of (Irianto, 2023) presented a design to analyze electrical energy consumption using IoT technologies, with a focus on prepaid smart systems. The implementation of the concept was conducted while adhering to the established prepaid power meter systems established by the

SEC, without introducing any modifications. A KWH meter tool has been devised, integrating IoT technologies, to compute and manage electricity consumption. The findings indicated that the implementation of the system enabled users to conveniently access and track their everyday consumption of electricity.

3. Methodology

3.1 Intelligent Power Management and Measurement

The power measurement entails the computation of both the real and the virtual elements of the periodic alternating current (AC) input voltage. If the voltage positive-cycle crossing the zero is seen at any given time relative to the referencing number, then subsequent to current positive-cycle zero is observed at a wave angle either smaller or larger than this referencing amount at a different time instant. The presence of a dominant current will result in the occurrence of the zero-crossing. The calculation of immediate energy is derived from the present values of V and I, and it was designed to represent the RMS.

The best method for determining AC power is using this particular technique. The results provide precise numbers across all dimensions of the load situation. The presence of additional harmonics in a non-linear system will have a significant impact on the shape of the output current waveform. The voltage-current phase angle, denoted as q, indicates an error of 30 degrees. The amount of power available at any given moment of time is determined by the product of the present voltage and simultaneous current across an element. The equations shown below depict the calculation of instantaneous power for sinusoidal voltage and current.

$$V_{int} = f \ \sqrt{2}Fsin \ (2\pi es) \tag{1}$$

$$I_{int} = f\sqrt{2}Isin \ (2\pi es - \theta) \tag{2}$$

$$O = 2 \ EIsin \ (2\pi es)\sin(2\pi es - \theta) \tag{3}$$

3.2 Three-Phase Energy Meter Functioning Principles

It is comprised of many essential components, including a microprocessor, voltage sensor, current sensor, SMPS system, and liquid crystal display (LCD)screen. The following subsection provides a block-wise discussion of its concept of the suggested energy meter. The primary sensing devices employed in this study are the current sensor (ACS712) and the voltage sensor (ZMPT101), illustrated in Figure1. Energy measuring integrated circuits (ICs), equipped with built-in digital signal processing (DSP) processors, enable the calculation of several variables.

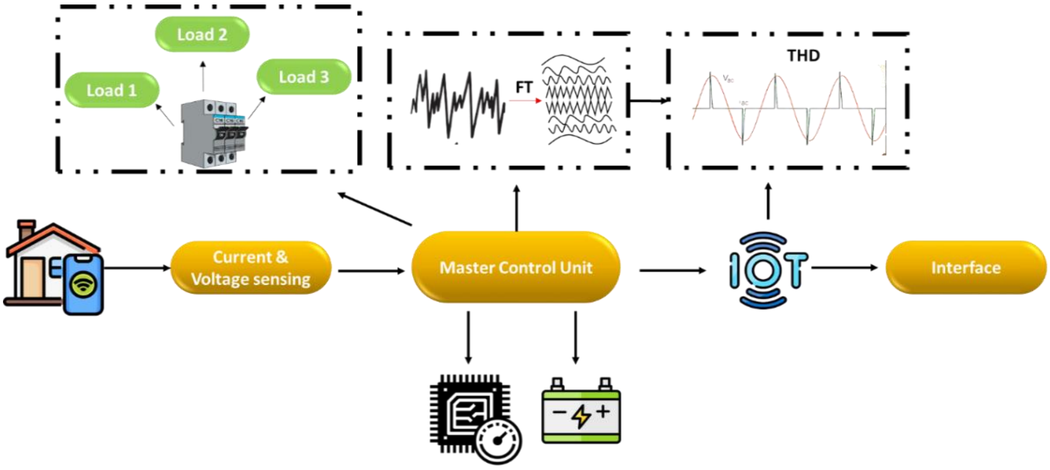


Figure 1: Smart energy meter

The utilization of the microcontroller serves the function, hence resulting in savings on expenses. The output of the V and I sensor is transmitted to the microcontroller unit (MCU), which analyzes the data and presents the results screen. In order to achieve this objective, the ATMEGA2560 microcontroller is employed and the relevant characteristics are demonstrated on a LCD with dimensions of 20 columns by 4 rows. A GSM module has the capability for establishing connection. Load break controls are to be used in order to regulate certain loads based on their energy usage. The IoT provides as a central component in the system interface, facilitating remote control and monitoring of systems. Measurement: The interface components are constructed with the Proteus program. The present measuring circuit utilizes the Allegro ACS712 sensor, demonstrated in Figure2. The ACS712 is a linear current sensor that is employed for the purpose of detecting both AC and direct current (DC) electrical currents. The ACS712-30A has been used for the purpose of measuring currents within the range of ±30 A. It has an output sensitivity of 66 mV/A when supplied with a voltage of +5 V.

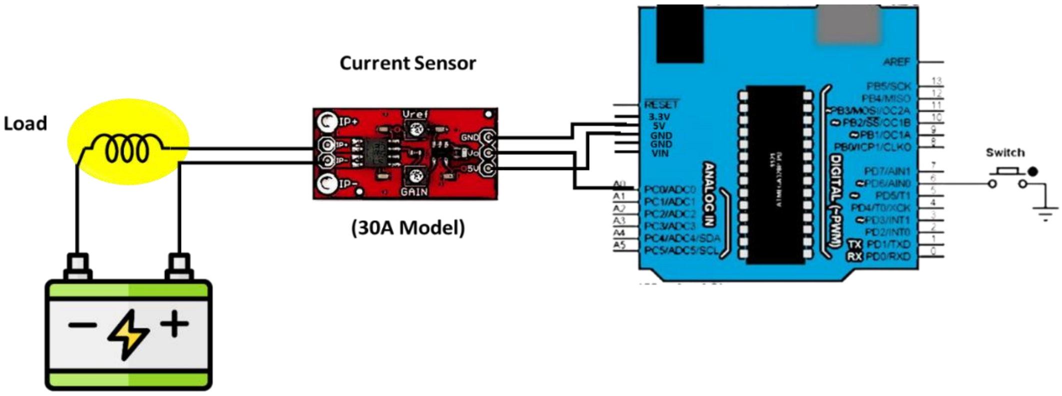


Figure 2: Model of Current Sensor

The voltage sensor utilized in this study is the ZMPT101B, displayed in Figure3. The device has been engineered to quantify the upper limit of AC voltage, with the limit set at a value below 250 V.

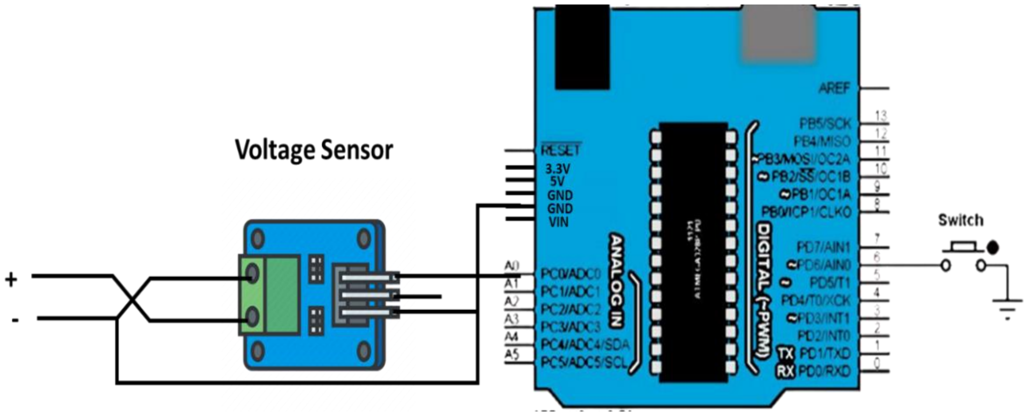


Figure 3: Model of voltage sensor

The signal produced by the circuit is linked to the analog-to-digital converter (ADC) pin of the microcontroller. The purpose of the model is to replicate the behavior of the current sensor, using a combined filter. This filter mechanism serves to decrease the noise present in the alternating current harmonic signal as mentioned in Table 1.

Table 1: Interfacing Circuits and Components

COMPONENTS	TYPE	PURPOSE	SPECIFICATIONS
VOLTAGE SENSOR	ZMPT101B	Voltage Sensing	- Measures AC voltage (< 250 V)
MICROCONTROLLER	ATMega328p	Signal Processing and Control	- ADC pin for interfacing with sensors
COMPARATOR CIRCUIT	LM324	Voltage Division	- Part of the voltage divider circuit
DIODE	1N4007	Rectification	- Used in the voltage divider circuit
RESISTORS	100 kΩ (x3)	Voltage Division	- Part of the voltage divider circuit

Calculating THD: The meter calculates the RMS values of current and voltage for every single phase. The calculation involves the incorporation of the real and the virtual parts of the V and I measurements in order to generate the RMSV and THD measurements that are then sent to the monitor mechanism. The metering technology provides measurements of voltages, four currents, actual power, reactive power, perceived power, and power factor. The FT is employed for the computation of precise root mean square values. The parameters of the Fourier transform are determined by leveraging the features of the FFT. The measurement of V and I in the range of frequency evaluation area has great significance. The time signal undergoes a transformation into the frequency signal by the implementation of the FFT, a computational approach. The primary principle of the energy metering technology centered on the effective use of the features of the Fast Fourier Transform for the estimation of coefficients. The technique used in this study utilizes radix 4 decimations in frequency (DIF). The procedure used in this approach utilizes the radix 4 technique for the computation of twiddle factors.

$$X_M^{ml} = f^{-i2\pi ml/M} \qquad (4)$$

$$W(m) = W(l) = \sum_{m=0}^{M-1} w(m) * X_M^{ml} * 100 \qquad (5)$$

RMSV Calculation: The determination of RMS voltage and current provides significant challenges throughout the development process of an energy meter. The RMSV is composed of both real and virtual components. The twiddle factor is multiplied by $w(m)$ to determine it. The amplitude of the AC signal, denoted as $w(m)$ is constrained in the range of $0\ to\ N-1$ numbers throughout the measurement procedure. The RMS voltage can be obtained by summing the actual and the virtual components of the subsequent RMS values in the range of $N/2-1$ repetitions in the current, as well as by summing the actual and virtual portions of the voltage levels. The magnitude of the direct current (DC) signal necessary to generate the equivalent RMS voltage of the AC signal is needed.

$$VRMS = \sqrt{\sum_{L=1}^{\frac{M}{2}-1} \left(V_{QF}(l) + V_{JN}(l)\right)} \qquad (6)$$

$$IRMS = \sqrt{\sum_{L=1}^{\frac{M}{2}-1} \left(I_{QF}(l) + I(_{JN}(l)\right)} \qquad (7)$$

HW method: The energy performance is determined by the presence of harmonics (H) with the signal. The presence of H in a signal develops a result of significant variations in the $I\ and\ V$ patterns while operating under non-linear load circumstances. In the present context, the assessment of power monitoring is impacted by the presence of H. The conventional HEM, which incorporates H evaluation and utilizes conventional DFT techniques, has some limitations. Various windowing strategies could be used to minimize the issue of spectral leaking in the harmonic characteristics of a signal. The approach under consideration incorporates the harmonic analysis procedure, which encompasses the use of HW techniques and certain interpolation procedures to improve the signal amplitude, hence facilitating realistic computation of URMS. The inclusion of cosine window approaches in the windowing process facilitates the generation of a superior side-lobe with enhanced quality. The frequency response, denoted as H(S), is determined by evaluating the transfer function of $w(m)$and $x(m)$. The symbol W(k) denotes the W weighting factor. The provided function is capable of exactly correcting the peaks, regardless of the data window employed in the signal frequency response. The initial signal is amplified by the window function, with both signals representing voltage and presently being retained in the buffer. The equation $V(l) = x(l), V(l)$ represents the relationship between $V(l)$, the voltage sample signal, and $x(l)$, the window weighting factor. The subsequent procedure is the computation of the FFT for $V(l)$. This entails the multiplication of the twiddle factor with the $V(l)$ signal. The complex voltage $V(l)$encompasses both the actual and virtual components, and is defined throughout the range of $0 \ to \ N-1$, where N is the total number instances present in the “sinusoidal signal”. The computation of “power spectrum densities and energy spectrum” densities are required for all types of harmonic energy meters. The computation of power spectral density is used to compensate for amplitude variations, whereas “energy spectral density” is employed to compensate for energy variations depending on the window function. The use of the Fourier transform also serves to mitigate the occurrence of leakage errors in the RMS V and I signal. The calculation of the actual and virtual components of V and I signal is utilized in the THD calculation. The procedure requires combining the ratios between the lth H of the actual and virtual components of the signal and the basic actual and virtual values of the V and I signal. The lth harmonics have the potential to represent the most powerful components of the signal. The Lrange performs a transition from $1 \ to \ N/2-1$, while the duration of the signal fluctuates in accordance with the magnitude values.

$$THDU = \sqrt{\sum_{L=1}^{\frac{m}{2}-1} \frac{\left(V_{QF}^{2}(l)+V_{JN}^{2}(l)\right)}{\left(V_{QF}^{2}(1)+V_{JN}^{2}(1)\right)} * 100} \tag{8}$$

$$THDI = \sqrt{\sum_{L=1}^{\frac{m}{2}-1} \frac{\left(J_{QF}^{2}(l)+J_{JN}^{2}(l)\right)}{(J_{QF}^{2}(1)+J_{JN}^{2}(1))} * 100} \tag{9}$$

$J_{QF}(l)$and$V_{QF}(l)$represent the actual harmonic factors of voltage and current, whereas $J_{JN}(l)$ and $V_{JN}(l)$ denote the virtual harmonic factors of voltage and current. Three voltage sensors are individually attributed to the three phases to measure the voltage of each phase. These sensors are configured to have the identical off level. The “Hall Effect sensor is used for the precise measurement” of I in the AC primary.

Formulation of FFT Technique: The approach determines the overall effect of H through utilizing the square root function to the actual and virtual components of V and I. The sampling variables involve even and odd values within the lthlevel harmonics of the overall H distortion. The polynomial calculation approach is employed for the estimation of the total H distortion. Figure 4 presents a sequence of steps describing the process of calculating THD and power through the FFT technique. This diagram represents the relationship between V and I samples in the frequency range, and demonstrates this connects to the features of the HW. Additionally, it highlights the use of actual and virtual components of the signal. A comprehensive exposition of the finite response of impulses associated with the FFT algorithm-based extrapolation technique is required, followed by a detailed account of the meter. The procedure provides simulated values of harmonic voltage and current as $V(l)$ and $I(l)$ correspondingly. The given entity may be partitioned into two distinct components, notably the real and imaginary sections. These components can be obtained by leveraging the characteristics of the FFT, as well as the number of samples, which is equal to $N/2-1$ for the variables $V\ and\ I$.

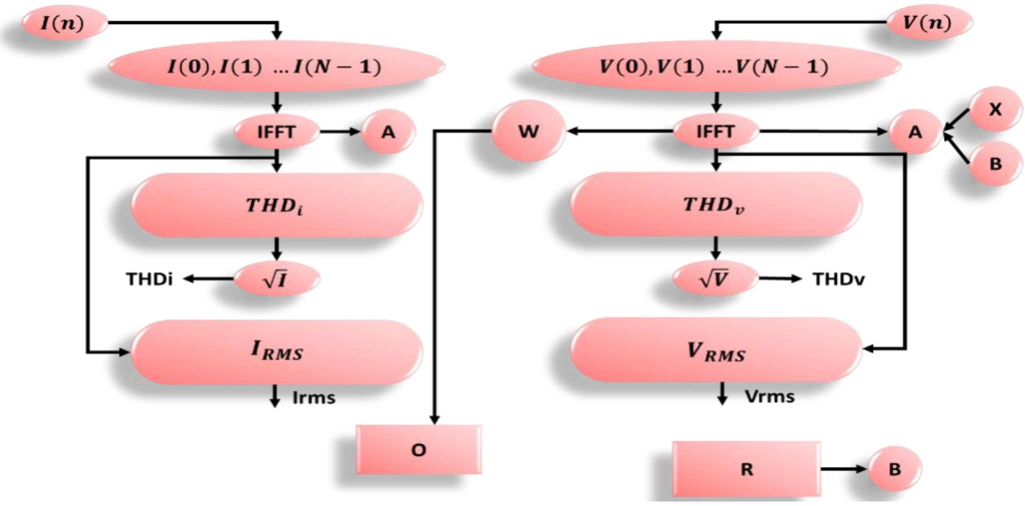


Figure 4: Smart energy meter methodology

Node-RED IoT Infrastructure: The open-source software, Node-RED, has the capability to support the IoT infrastructure. In order to obtain the diverse data provided by the energy meter, it is necessary for users to create and log into a user account on this system. To ensure the safe transmission of data to a cloud-based system using Node-RED, it is necessary to establish API key credentials and define the server URL. Node-RED, being an open-source platform, demonstrates exceptional proficiency in supporting the confidential and protected transport of data to cloud servers. In addition, this feature facilitates the seamless generation and integration of API keys inside the product. The purpose of this network is to gather sensor data. In order to contribute data to a cloud-based system, it is recommended that users establish an account inside the Node-RED platform.

3.3 Smart Electric Meter

The conventional energy meter provides information on the hourly energy use and associated billing information. Figure5 illustrates the functionality of an IoT enabled energy meter, which is capable of transmitting actual time energy consumption data to a cloud-based system. Additionally, the meter is equipped with the capability to facilitate payment for energy consumption through the utilization of IoT technology. The primary objective of this system is to facilitate the advance notification of power parameter scheduling and to provide an alert mechanism that generates a message when the electric energy usage above certain threshold levels. Additionally, it has provisions to discontinue power distribution while individuals are absent from the station to mitigate energy overflow.

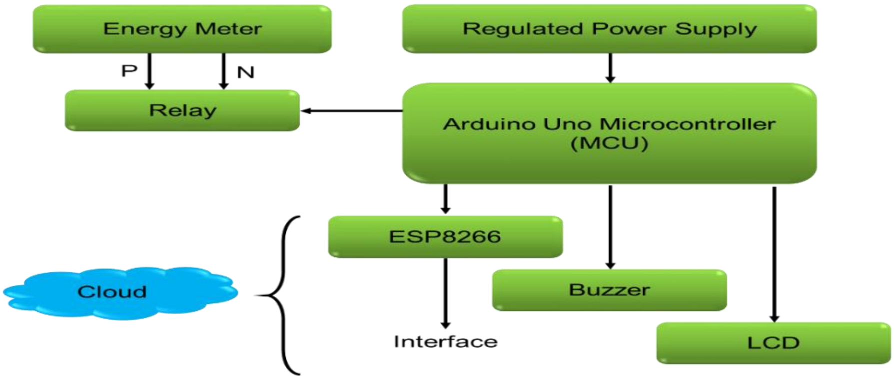


Figure 5: Smart Energy Meter Structure

The ESP8266 chip serves as the Wi-Fi module utilized for transmitting data updates to an online server over the internet. There are other open source tools available that resemble cloud-based platforms, such as Node-RED and FIWARE tools. If the data transmission to the cloud is not feasible, an alternate method would include using a wireless 4G module GSM to deliver the data as an SMS service to the designated recipients. Communications may be established by use of AT commands, facilitating the transmission of messages. Various instructions from AT are used to execute distinct tasks to achieve the monitoring condition and sensor data for the meters. The simulation module outcomes indicate that the GSM modem serves as an acceptable platform for monitoring energy meters. The simplified model of smart meter's deployment is demonstrated in Figure6.

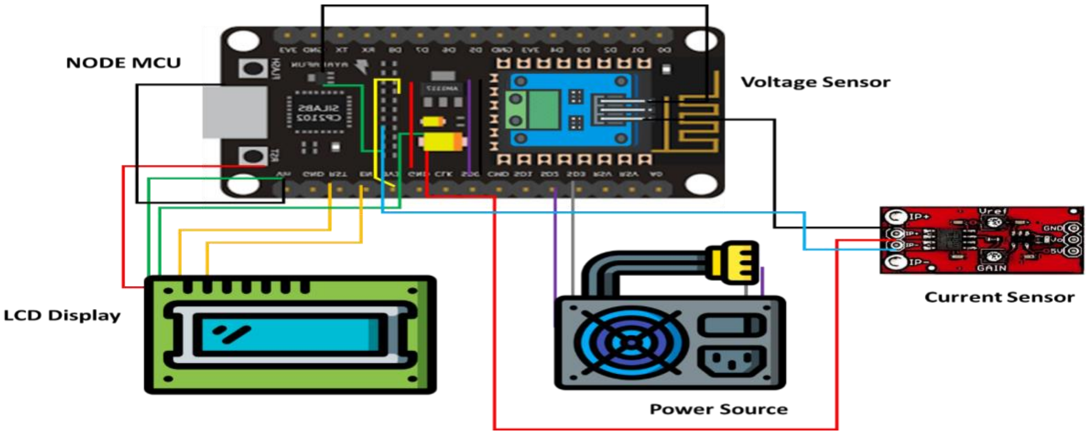


Figure 6: Simplified model of smart meter

4. Finding evaluation

4.1 Sample Procedure

Samples refers to the procedure of transforming a “constant Time-H signal into a discrete-time H signal.” The microcontroller is provided with four sets of difference inputs for the purpose of calculating voltage and current. The analog channel contains the ability to adjust the voltage gain phase programmatically. The resultant signal is then transformed through the application of approximation steps approaches, which require the variance of the input voltage subsequent to the analog-to-digital conversion process.

The analog channel is configured using the Analog Read function in the Arduino IDE. All channels are attached to a shared “negative terminal, “while any additional ADC inputs in that section may be chosen as the “positive input terminal.” The waveform seen here illustrates the presence of both moderate and significant harmonics within the signal output. Figure7 above shows the signal of H for scenarios with both weak and strong magnitudes. In the context of practical observation, the frequency of the system's electricity supply exhibits a range of fluctuation between 49 and 50 Hz.

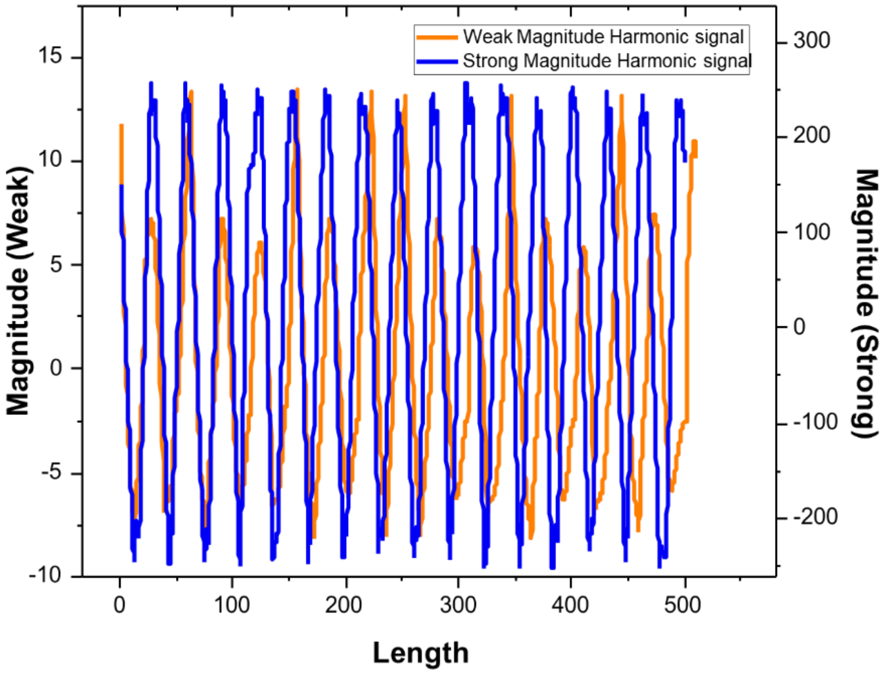


Figure 7: Harmonics signals

A comparison study was conducted to compare the findings produced from the IFFT with those gathered using the traditional DFT methods and traditional FFT such as Fluke 87V, Fluke 941, Megger LT300. A comparative analysis was conducted between normal meters and the smart meter that we have established. Based on the statistics summarized in Tables2-4 and displayed in Figure 8, it can be deduced that the MECO meter exhibits a voltage harmonics error percentage of 3.7%, whereas the Fluke 434 m has a lower error of 1.54%.

In a comparative analysis, it was demonstrated that the MECO meter exhibits a percentage variation of 4.6% for current H, whereas the Fluke 434 m has a lower percentage deviation of 0.48%. Additionally, the highest acceptable level for odd harmonic currents is set at 4% for harmonics up to the 11th order, provided that the current does not exceed 20 amperes.

Table 2: Standard meters and smart energy meter

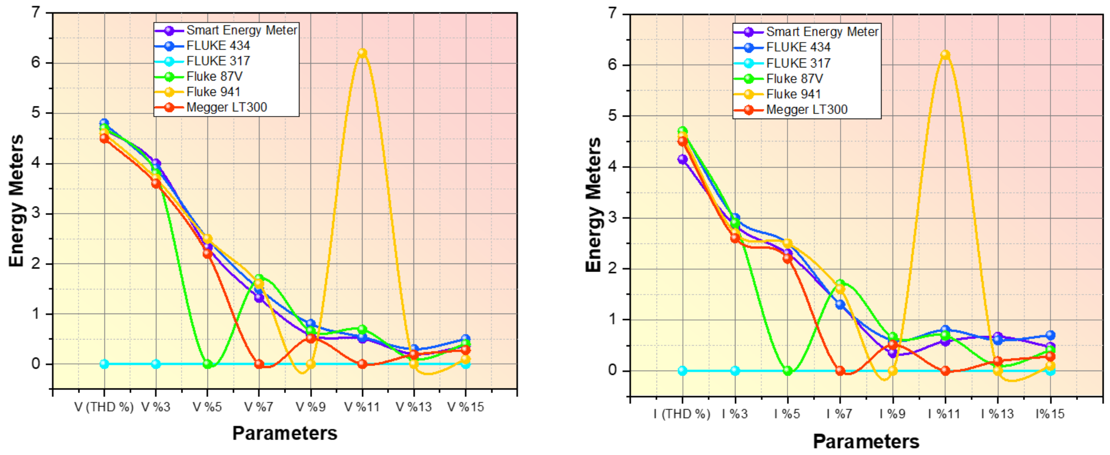
PARAMETERS	MECO PLH5760	FLUKE 317	FLUKE 434	FLUKE 87V	FLUKE 941	MEGGER LT300	SMART ENERGY METER
VRMS	221.1	222	223	221.5	222.3	22.1	223
IRMS	1.315	1.5	1.9	1.326	1.235	1.3	1.33
P(KW)	0.289	-	0.37	0.35	0.21	0.16	0.287
Q(KVAR)	0	-	0.06	0.023	0.05	0	0.059
S(KVA)	0.291	-	0.39	0	0.16	0.29	0.31
P.F	1.01	-	1.00	1.23	1.02	0.2	01.00

Table 3: Standard meters and smart energy meter

PARAMETERS	FLUKE 434	FLUKE 87V	FLUKE 317	FLUKE 941	SMART ENERGY METER	MEGGER LT300
V (THD %)	4.8	4.7	0	4.6	4.69	4.5
V %3	3.9	3.8	0	3.7	4	3.6
V %5	2.5	0	0	2.5	2.33	2.2
V %7	1.5	1.7	0	1.6	1.32	0
V %9	0.8	0.66	0	0	0.58	0.51
V %11	0.54	0.69	0	6.2	0.51	0
V %13	0.3	0.1	0	0	0.2	0.19
V %15	0.5	0.4	0	0.1	0.36	0.28

Table 4: Standard meters and smart energy meter

PARAMETERS	FLUKE 317	FLUKE 87V	FLUKE 434	FLUKE 941	MEGGER LT300	SMART ENERGY METER
I (THD %)	0	4.7	4.7	4.6	4.5	4.15
I %3	0	2.9	3	2.7	2.6	2.85
I %5	0	0	2.5	2.5	2.2	2.3
I %7	0	1.7	1.3	1.6	0	1.3
I %9	0	0.66	0.6	0	0.51	0.35
I %11	0	0.69	0.8	6.2	0	0.58
I %13	0	0.1	0.6	0	0.19	0.67
I%15	0	0.4	0.7	0.1	0.28	0.47



(A) (B)

Figure 8: Standard meters and smart energy meters (A) Voltage (B) Current

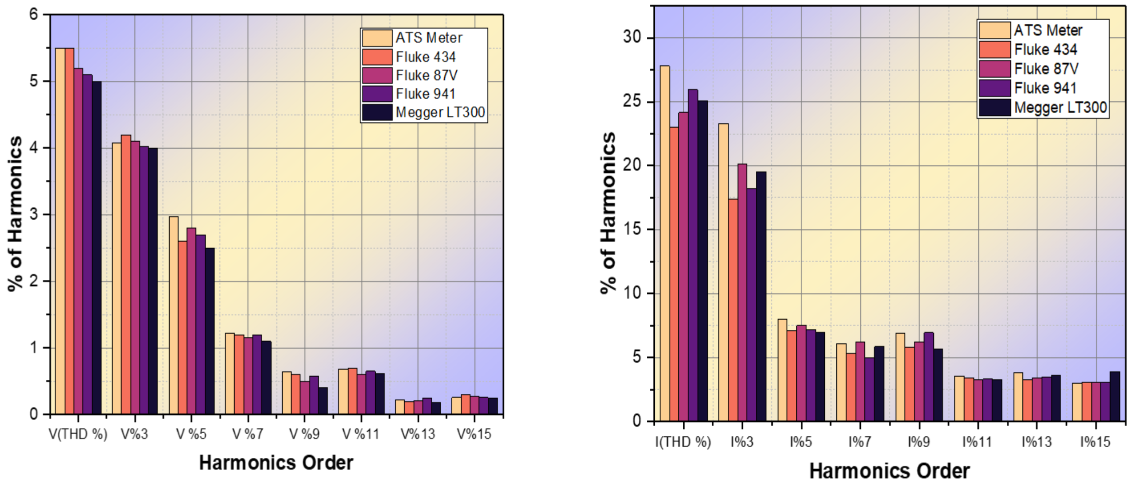
This paper discusses the proportion of voltage harmonics composition inside the signal, which has the potential to impact the functioning of the energy meter. The comparison conducted among the “calibration meter and the most basic harmonics” reveals a much higher percentage in contrast to other harmonic systems. Figure 9provides an illustration of the proportion of current harmonics included within the signal, which has the potential to disrupt the operational efficiency of the energy meter as mentioned in Tables 5 and 6.

Table 5: Harmonics (Voltage)

PARAMETERS	ATS METER	FLUKE 434	FLUKE 87V	FLUKE 941	MEGGER LT300
V(THD %)	5.5	5.5	5.2	5.1	5
V%3	4.07	4.2	4.1	4.03	4
V %5	2.97	2.6	2.8	2.7	2.5
V %7	1.22	1.2	1.15	1.19	1.1
V %9	0.64	0.6	0.5	0.58	0.4
V %11	0.68	0.7	0.6	0.65	0.62
V%13	0.22	0.2	0.21	0.25	0.18
V%15	0.26	0.3	0.27	0.26	0.25

Table 6: Harmonics (Current)

PARAMETERS	ATS METER	FLUKE 434	FLUKE 87V	FLUKE 941	MEGGER LT300
I(THD %)	27.8	23	24.15	25.94	25.1
I%3	23.27	17.4	20.15	18.23	19.52
I%5	8.035	7.1	7.5	7.2	7
I%7	6.11	5.3	6.2	5	5.85
I%9	6.88	5.8	6.25	6.94	5.7
I%11	3.56	3.4	3.3	3.34	3.3
I%13	3.79	3.3	3.4	3.5	3.6
I%15	3	3.1	3.05	3.06	3.9



(A)

(B)

Figure 9: Harmonics (A) Voltage (B) Current

4.2 Potential Risks in Smart Meters

When implementing smart meters, it is crucial to recognize and avoid many substantial cybersecurity vulnerabilities. One important issue is on the inherent weaknesses found in communications protocols that facilitate the interaction between smart meters and household equipment. These weaknesses make the systems susceptible to possible cyber assaults, hence requiring the implementation of strong security measures. Moreover, it is important to highlight the significant danger surrounding the prevalent use of unfavorable incentive structures by service providers. The prioritization of reducing expenses above security might render smart meter implementations vulnerable to intrusions and breaches of data integrity. An additional problem arises due to the recurrent constraint of professionals with the requisite skills to proficiently assess and administer these security threats in an exact way. In addition, the separation of smart meter operations from the responsibility of grid operators, especially in industrialized nations, presents a barrier to the improvement of comprehensive safety and security. In instances of cybersecurity attacks, it becomes imperative to establish precise definitions of duty and responsibilities, since the delineation of culpability may be imprecise. The mitigation of these potential risks of utmost importance to assure the seamless incorporation of smart meters into our growing interconnected and digital electrical systems.

5. Conclusion

The adoption of smart energy meter technology equipped with Internet of Things (IoT) capabilities marks a significant advancement for sports facilities striving to enhance their operational efficiency and sustainability. This study demonstrates that integrating an Improved Fast Fourier Transform (IFFT) with advanced measurement techniques like Total Harmonic Distortion (THD)

Computing and Root Mean Square Voltage (RMSV) significantly improves the precision and reliability of energy management within sports environments. In sports facilities, where the demand for energy can vary dramatically due to scheduled events, training sessions, and maintenance operations, having a robust energy management system is crucial. The smart energy meters, by providing real-time, accurate energy usage data, enable facility managers to optimize power consumption and reduce costs without compromising the quality of conditions provided for both athletes and spectators. This is particularly important in sports where environmental conditions, such as lighting and temperature, can directly influence athletic performance and the overall experience for attendees. Furthermore, the use of the Hanning Window (HW) method for more reliable harmonic analysis ensures that sports facilities can prevent power quality issues that might otherwise damage high-cost training equipment or disrupt heavily scheduled events. The stability provided by these smart meters supports the longevity of facility infrastructures and reduces the risk of unexpected downtime or costly repairs. Implementing Node-RED for seamless data management not only streamlines operations but also empowers sports organizations to make data-driven decisions that align with energy conservation goals and financial strategies. The comparative analysis presented in this study illustrates that smart meters not only outperform traditional methods in terms of efficiency but also contribute to a sustainable sports management practice by significantly lowering energy waste and environmental impact. Given the positive outcomes observed, it is recommended that sports facility operators consider the strategic implementation of smart energy meter systems. Such technology is not merely an operational upgrade; it is a crucial component in fostering a high-performance, sustainable sports environment. Future investigations should aim to quantify the specific impacts on athletic training outcomes and explore the integration of renewable energy sources with smart metering to further enhance the sustainability profiles of sports facilities.

Acknowledgement

Fund: (Science and Technology Project, Analysis and Research on Standard Performance Automatic Verification Technology of Electric Energy Meter Automatic Verification System, 035900KK52220011). Southern Power Grid Corporation Technology Project Support (Project Number: [035900KK52220011 (GDKJXM20220876)].

Reference

Abate, F., Carratù, M., Liguori, C., & Paciello, V. (2019). A low cost smart power meter for IoT. *Measurement, 136*, 59-66.

Ahammed, M. T., & Khan, I. (2022). Ensuring power quality and demand-side management through IoT-based smart meters in a developing country.

Energy, 250, 123747.

Akkad, A., Wills, G., & Rezazadeh, A. (2023). An information security model for an IoT-enabled Smart Grid in the Saudi energy sector. *Computers and Electrical Engineering, 105*, 108491.

Albatayneh, A., Juaidi, A., Abdallah, R., Pena-Fernandez, A., & Manzano-Agugliaro, F. (2022). Effect of the subsidised electrical energy tariff on the residential energy consumption in Jordan. *Energy Reports, 8*, 893-903.

Barman, B. K., Yadav, S. N., Kumar, S., & Gope, S. (2018). *IOT based smart energy meter for efficient energy utilization in smart grid.* Paper presented at the 2018 2nd international conference on power, energy and environment: towards smart technology (ICEPE).

Bera, B., Saha, S., Das, A. K., & Vasilakos, A. V. (2020). Designing blockchain-based access control protocol in IoT-enabled smart-grid system. *IEEE Internet of Things Journal, 8*(7), 5744-5761.

Buonomano, A., Barone, G., & Forzano, C. (2022). Advanced energy technologies, methods, and policies to support the sustainable development of energy, water and environment systems. In (Vol. 8, pp. 4844-4853): Elsevier.

Chaudhuri, A., Datta, R., Kumar, M. P., Davim, J. P., & Pramanik, S. (2022). Energy conversion strategies for wind energy system: Electrical, mechanical and material aspects. *Materials, 15*(3), 1232.

Elsisi, M., Mahmoud, K., Lehtonen, M., & Darwish, M. M. (2021). Reliable industry 4.0 based on machine learning and IOT for analyzing, monitoring, and securing smart meters. *Sensors, 21*(2), 487.

Froiz-Míguez, I., Lopez-Iturri, P., Fraga-Lamas, P., Celaya-Echarri, M., Blanco-Novoa, Ó., Azpilicueta, L., . . . Fernández-Caramés, T. M. (2020). Design, implementation, and empirical validation of an IoT smart irrigation system for fog computing applications based on Lora and Lorawan sensor nodes. *Sensors, 20*(23), 6865.

Irianto, K. D. (2023). Pre-SEMMS: A Design of Prepaid Smart Energy Meter Monitoring System for Household Uses Based on Internet of Things. *Journal of Electronics, Electromedical Engineering, and Medical Informatics, 5*(2), 69-74.

Iwendi, C., Maddikunta, P. K. R., Gadekallu, T. R., Lakshmanna, K., Bashir, A. K., & Piran, M. J. (2021). A metaheuristic optimization approach for energy efficiency in the IoT networks. *Software: Practice and Experience, 51*(12), 2558-2571.

Jabbar, W. A., Annathurai, S., Rahim, T. A. A., & Fauzi, M. F. M. (2022). Smart energy meter based on a long-range wide-area network for a stand-alone photovoltaic system. *Expert Systems with Applications, 197*, 116703.

Jain, R., Gupta, S., Mahajan, C., & Chauhan, A. (2019). Research paper on IOT based smart energy meter monitoring and controlling system. *Int. J. Res.*

Electron. Comput. Eng, 7(2), 1600-1604.

Jain, S., Pradish, M., Paventhan, A., Saravanan, M., & Das, A. (2018). *Smart energy metering using LPWAN IoT technology.* Paper presented at the ISGW 2017: Compendium of Technical Papers: 3rd International Conference and Exhibition on Smart Grids and Smart Cities.

Karpagam, M., Sahana, S., Sivadharini, S., & Soundhariyasri, S. (2023). *Smart Energy Meter and Monitoring System using Internet of Things (IoT).* Paper presented at the 2023 International Conference on Intelligent Data Communication Technologies and Internet of Things (IDCIoT).

Kumar, A., Alghamdi, S. A., Mehbodniya, A., Webber, J. L., & Shavkatovich, S. N. (2022). Smart power consumption management and alert system using IoT on big data. *Sustainable Energy Technologies and Assessments, 53*, 102555.

Li, F., Shi, Y., Shinde, A., Ye, J., & Song, W. (2019). Enhanced cyber-physical security in internet of things through energy auditing. *IEEE Internet of Things Journal, 6*(3), 5224-5231.

Mahapatra, B., & Nayyar, A. (2022). Home energy management system (HEMS): Concept, architecture, infrastructure, challenges and energy management schemes. *Energy Systems, 13*(3), 643-669.

McWilliams, J. M., Weinreb, G., Ding, L., Ndumele, C. D., & Wallace, J. (2023). Risk Adjustment And Promoting Health Equity In Population-Based Payment: Concepts And Evidence: Study examines accuracy of risk adjustment and payments in promoting health equity. *Health Affairs, 42*(1), 105-114.

Meeks, R. C., Omuraliev, A., Isaev, R., & Wang, Z. (2023). Impacts of electricity quality improvements: Experimental evidence on infrastructure investments. *Journal of Environmental Economics and Management*, 102838.

Mudaliar, M. D., & Sivakumar, N. (2020). IoT based real time energy monitoring system using Raspberry Pi. *Internet of Things, 12*, 100292.

Parvin, K., Hannan, M., Mun, L. H., Lipu, M. H., Abdolrasol, M. G., Ker, P. J., . . . Dong, Z. (2022). The future energy internet for utility energy service and demand-side management in smart grid: Current practices, challenges and future directions. *Sustainable Energy Technologies and Assessments, 53*, 102648.

Pawar, P., & TarunKumar, M. (2020). An IoT based Intelligent Smart Energy Management System with accurate forecasting and load strategy for renewable generation. *Measurement, 152*, 107187.

Rezaeimozafar, M., Monaghan, R. F., Barrett, E., & Duffy, M. (2022). A review of behind-the-meter energy storage systems in smart grids. *Renewable and Sustainable Energy Reviews, 164*, 112573.

Rostampour, S., Bagheri, N., Ghavami, B., Bendavid, Y., Kumari, S., Martin, H., & Camara, C. (2023). Using a Privacy-Enhanced Authentication Processto Secure IoT-based Smart Grid Infrastructures.

Saleem, M. U., Shakir, M., Usman, M. R., Bajwa, M. H. T., Shabbir, N., Shams Ghahfarokhi, P., & Daniel, K. (2023). Integrating smart energy management system with internet of things and cloud computing for efficient demand side management in smart grids. *Energies, 16*(12), 4835.

Singh, S., & Yassine, A. (2019). *IoT big data analytics with fog computing for household energy management in smart grids.* Paper presented at the Smart Grid and Internet of Things: Second EAI International Conference, SGIoT 2018, Niagara Falls, ON, Canada, July 11, 2018, Proceedings 2.

Veskioja, K., Soe, R.-M., & Kisel, E. (2022). Implications of digitalization in facilitating socio-technical energy transitions in Europe. *Energy Research & Social Science, 91*, 102720.

Yang, Q., & Wang, H. (2021). Privacy-preserving transactive energy management for IoT-aided smart homes via blockchain. *IEEE Internet of Things Journal, 8*(14), 11463-11475.