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Enhancing Protection and Monitoring in Modern Distribution Systems Using Smart Meter: A Review

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Abstract

Distribution systems are witnessing a significant increase in the deployment of smart meters (SMs). Though some remain hesitant about adopting SMs due to concerns related to health risks from radio wave exposure, fire hazards, and the privacy of user data. Additional key issues are high cost for energy suppliers, with perceived fewer advantages, as highlighted in detailed cost-benefit analyses. In some instances, existing SM applications have failed to justify their value. Numerous reports suggest that global SM rollouts have faced various challenges, leading to slow progress and rising skepticism. This has created a need for expanding the use of SMs, particularly in areas like monitoring and protection within evolving electrical networks. Protection and monitoring are critical concerns for distribution providers, and they are eager to explore smart solutions to manage these functions effectively. This paper proposes several potential uses of SMs to enhance the safety and reliability of distribution systems, with the expectation that these innovations will help validate and encourage future smart metering projects.

Keywords: Smart meters, distribution system protection, Power system monitoring, Grid reliability, Advanced metering infrastructure (AMI)

INTRODUCTION

Globally, other service providers in the electrical sector are shifting from conventional operations to automated and remote control systems. The idea of "smart grids" plays a crucial part in this transformation, ensuring secure, high-quality, and economically efficient electrical energy in a competitive space. In terms of generation, there is a shift from large, centralized power generation to smaller, decentralized power generation, which is known as the distributed generation of electrical energy. This evolution is driven by digitalization and advancements in Internet of Things (IoT) technologies. Smart meters (SMs) are central to integrating distribution generation into evolving electrical networks. SMs can be described as advanced metering devices capable of recording energy consumption every 15 min, which is transferred to utility companies in real-time recording scenarios. They also permit two-way communication within utility companies and SMs, allowing remote control functionalities, such as disconnecting energy delivery.

Several countries are rapidly deploying SMs in their distribution networks. By the end of 2015, around 65 million SMs were installed in the U.S., accounting for over 50% of homes. This figure is expected to grow to 70 million by 2016, reaching approximately 90 million by 2020 [1]. With investments exceeding 32 billion USD, the 30 chief electrical industries in the USA have completely implemented SMs. In 2020, the European Union replaced conventional electric meters with SMs. Fourteen European nations, including Finland, Denmark, Austria, and Sweden, are on track to

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achieve 95% or higher penetration rates by 2020 [2]. Notably, Finland, Italy, and Sweden installed approximately 45 million SMs, representing nearly a quarter of the 2020 target. In the Netherlands, around 3 million households had SMs by the end of 2016, and the country is on course to meet the 80% target by 2020, supported by several European projects [3].

The Asia-Pacific region is the largest and fastest-growing area in the world for SMs, with an installed base of over 1.3 billion units. The annual demand for electricity meters in this region is between 110 million and 200 million units, with China alone accounting for approximately 70%. The Korea Electric Power Corporation deployed 8.8 million SMs nationwide by 2019, with 7 million installed in 2018 and additional units in 2019 [4]. The goal is to install 22.5 million SMs in South Korea by 2020. In India, state-owned Energy Efficiency Services Limited has announced plans to install 1 million SMs nationwide under the Government of India's Smart Meter National Program, and to install 250 million over the next few years. In the Asia-Pacific region, the SM penetration was 67% in 2018 and is expected to grow to 94% by 2024, driven largely by mass deployment in India [5].

Despite the widespread global adoption of SMs, they have consistently been the subject of controversy, largely sparked by the Wall Street Journal's article titled "Smart Meter, Dumb Idea?" Many concerns have been raised regarding features such as remote control capabilities, potential health risks from radio wave exposure, fire hazards, and the security and privacy of customer data [6]. Another significant issue is the increased cost for utility providers, as the deployment of SMs requires additional investments in hardware, software, and peripheral devices. This often leads to an overhaul of billing systems to fully capitalize on the benefits of SMs. Detailed cost-benefit analyses have fueled the argument that SMs are not cost-effective for many utility providers. Global rollout projects face numerous challenges and delays, hindering their implementation.

Existing applications of SMs include electricity theft detection, demand response and load scheduling, load modeling, load forecasting, state estimation, and outage management. However, these applications have not fully demonstrated the value of SMs in smart grids, which has led to slow progress in their adoption by distribution providers. This highlights the need to enhance SM applications, particularly in the areas of protection and monitoring within emerging distribution systems.

This study emphasizes the importance of discovering novel uses for SMs for electrical networks to better support cost-benefit analyses for upcoming planned projects. Monitoring and protection are critical concerns for any distribution provider, and there is growing interest in smart solutions for managing these aspects. This study suggests numerous potential uses for SMs to enhance electrical network reliability and protection, to provide the necessary justifications to encourage upcoming SM infrastructure. This work focuses on investigating new uses for smart meters for monitoring and protection, with the expectation that these advancements will help justify and encourage the future adoption of SM technologies.

1. Smart meter adoption for performance enhancement
2. Power monitoring and theft detection
3. Demand-side management and peak load reduction
4. Consumer engagement and behavior analysis
5. Cybersecurity and privacy concerns
6. Power quality and grid optimization

OVERVIEW OF ADVANCED METERING TECHNOLOGY

Smart Meter Components

Utility companies worldwide utilize SMs for commercial, household, and industrial use. Meter manufacturers and utility providers are continually improving SMs by incorporating advanced encryption techniques, new communication protocols, and semiconductor technology. Because SMs must comply with the regulatory standards of different regions, it is essential to develop a set of common hardware and firmware components that allow for modifications, as needed. The following sections describe the core building blocks of smart meters used to monitor and secure the operation of electrical networks.

Measurement and Processing Unit

A measurement-processing unit (MPU) is the central component that integrates a core processor with flash memory, enabling flexible configuration, data processing, and interaction with other systems. The MPU contains built-in analog-to-digital converters (ADCs) and digital signal processing capabilities that execute signal processing algorithms. It manages all energy metering responsibilities by cooperating with various peripherals, such as analog front-end (AFE) circuits, ADCs, ASICs, electrically erasable programmable read-only memories (EEPROMs), network interfaces, display units, timers, and interrupts. The MPU communicates with AFE chips via a serial interface such as serial peripheral interface (SPI) or I2C, whereas an application-specific integrated circuit (ASIC) provides digital registers to represent key factors such as energy consumption, RMS voltage and current, and frequency.

Storage Handling Unit

SMs are equipped with permanent storage, such as EEPROM, to retain conformation settings and power measurements passing through a cycle of energy. The storage can be an on-chip component or connected externally using the 12C and SPI interfaces. This memory can store key parameter data such as voltage, current, and energy (kWh, kVARh, kVAh), as well as calibration coefficients, device configurations, and logs of alarms or events, all with timestamp information.

Time Keeping Unit

The time keeping unit (TKU) consists of a real-time clock (RTC), a crucial component of the SMs. RTC timestamp events and alarms. To maintain accuracy during power outages, the RTC includes a battery backup system that switches between the main power source and the battery. This power switch can be activated by either hardware or firmware, and care must be taken to avoid delays in switching that can reset the RTC.

Communication Unit

A key feature of a smart meter is its capability to interconnect with electrical substations and electrical networks. Communication protocols such as DLMS/COSEM and Modbus were used to standardize data exchange. In addition, SMs support various interfaces, including SPI and I2C, which are convenient for connecting peripheral equipment. Some meters also provided an isolated RS-485 interface for serial communication.

User Interface Unit

The user interface unit (UIU) typically includes an LCD demonstration (often modified with a 7-segment format) to show settings for billing, configurations, diagnostics, and load surveys. Users can navigate the meter’s settings through the front panel buttons or set them to auto-scroll. The LED indicators on the panel also show energy consumption, calibration status, and communication connectivity.

Event Logging Unit

SMs incorporate event logging systems to track various activities such as power consumption and tampering attempts. These meters use two different measurement components for tracking power in the reverse and forward paths of the current, ensuring continued accurate readings even during external tampering attempts. Events such as neutral disconnections, magnetic tampering, and case openings are logged and recorded in the real memory of the SM.

Security Unit

SMs require robust communication security to protect the data transmission between the utility server and meter. Encryption and authentication algorithms ensure the privacy and integrity of the data. The security system also safeguards against physical tampering, both mechanical and electrical.

Configuration and Calibration Unit

Smart meters include a calibration and configuration unit (CCU) that manages different configuration settings, such as SM ratings, current transformer and potential transformer ratios, single to multi-phase topologies, pulse outputs, and message components. Users can adjust these settings remotely via the front panel using a transfer connection. The standardization of an SM is performed by adjusting the rated value of the current and voltage using external standard sources for voltage and current inputs.

Classification of Smart Meter

In modern distribution systems, various tools are now available to monitor and measure electrical parameters, categorized under the broad classification of SMs. These devices are increasingly being integrated into emerging smart distribution networks, significantly enhancing their system capabilities [7]. There are four main types of SMs: smart energy meters, smart feeder meters, and smart distributed transformer monitors. This section provides a brief overview of SEMs and SFMs.

Smart Energy Meters

Smart energy meters (SEMs) are electronic devices designed to save electrical energy demand and transfer this data to the electricity company for observation and billing determinations. These meters typically log energy usage hourly or at even shorter intervals and report it at least once per day. In addition to measuring energy, SEMs are capable of recording current, angle, and frequency, and steadily transmitting this information [8]. A key feature of SEMs is their ability to allow two-way data transfer within distribution network operators and meters by utilizing technologies such as cellular networks, wireless communication, and ZigBee. SEMs are used for user-side deployment to control and monitor appliances in a house. It also gathers analytic data on the electrical network and household devices and may contact the SMs within this range [9].

Smart Feeder Meters

The availability of electricity measurements, such as current and voltage, is increasing across distribution grids, offering improved grid visibility, which was previously unavailable. The ability of distribution system operators to monitor individual feeder currents at secondary substations is crucial for detecting grid congestion. Utilities have shown a growing concentration in electrical network computerization for nursing and controlling numerous feeder and substation devices, with primary demo developments proving the viability and advantages of such systems. While fitting more appliances to measure currents for electrical stations may be cost-prohibitive, the rising placement of smart feeder meters delivers operators with valuable insight into the currents of more users [10]. As the operation of smart feeder meters progresses, selecting, prioritizing, and integrating automated tasks, such as reconfiguration and restoration of feeder, bus voltage, and reactive power control, has become increasingly critical. However, methods to obtain dynamic information for on-site application of smart feeders are limited to very few electrical networks.

Monitoring and Assessment Capabilities

The latest production of SMs typically features an microcontroller unit (MCU) paired with an AFE connected by an ADC [4]. The construction site was equipped with a smart meter with advanced monitoring and assessment capabilities. Figure 1 shows the range of abilities that a smart meter generally includes or can potentially incorporate. Unlike traditional meters, modern SMs can measure not only real power but also other critical factors, such as reactive power, RMS value of voltage, current, power factor, and harmonic distortion. Additionally, beyond the smart functionality of automatically sorting electrical factors on a scheduled basis, modern SMs support various load monitoring determinations, including rolling blocks and predicted and synchronized loads.

Communication Features and Standards

For a modernized electrical network, where advanced technologies and applications are integrated, the vast amount of data collected by numerous SMs must be processed and analyzed efficiently. As such, communication lines are a vital part of SMs. Therefore, it is essential to describe the communication requirements and select the most suitable network to ensure protection, safety, reliability, and lucrative data transmission throughout the entire network. The chosen information transmission technology should be lucrative, offer a better transmission bandwidth, provide robust safety, and support sufficient range and electrical quality while minimizing the need for retransmissions. For SM applications, information may be transmitted using various means, including wire connections, electrical transmission lines, radio communication, and internet networks. Typically, the data sent through a smart meter ranges from 20 bytes to 500 bytes, with an average daily data transmission of approximately 3185 bytes to the grid operator [2]. An SM can usually transmit data up to three times per day, with smaller messages commonly sent every 15–60 min to the data concentrator. In high-frequency applications, messages can be sent every 5–10 min. Dedicated serial lines, such as metal-covered or uncovered warped pairs, less-cost RJ13 connections, or lower-level ISO layers, such as RS223, RS458, or USB, are often used to transfer information following simple and open communication protocols, such as IEC 62056-21 [8, 11–13]. This approach is economical, uses straightforward protocols, experiences low interference, and ensures enhanced data protection. However, it is less appropriate for long-range applications because of the associated costs and setup difficulty as shown in Figure 2 and Table 1.

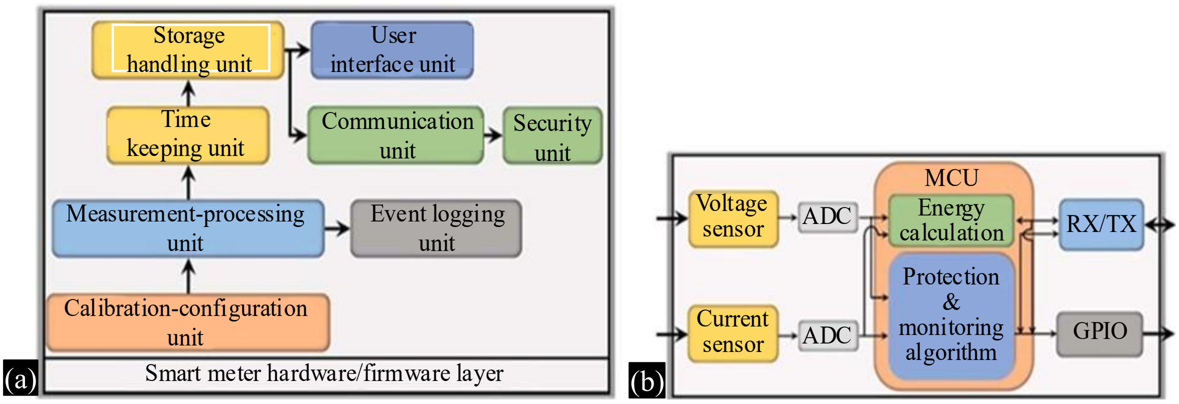

Figure 1. (a) and (b) Structure of advanced SMs [9].

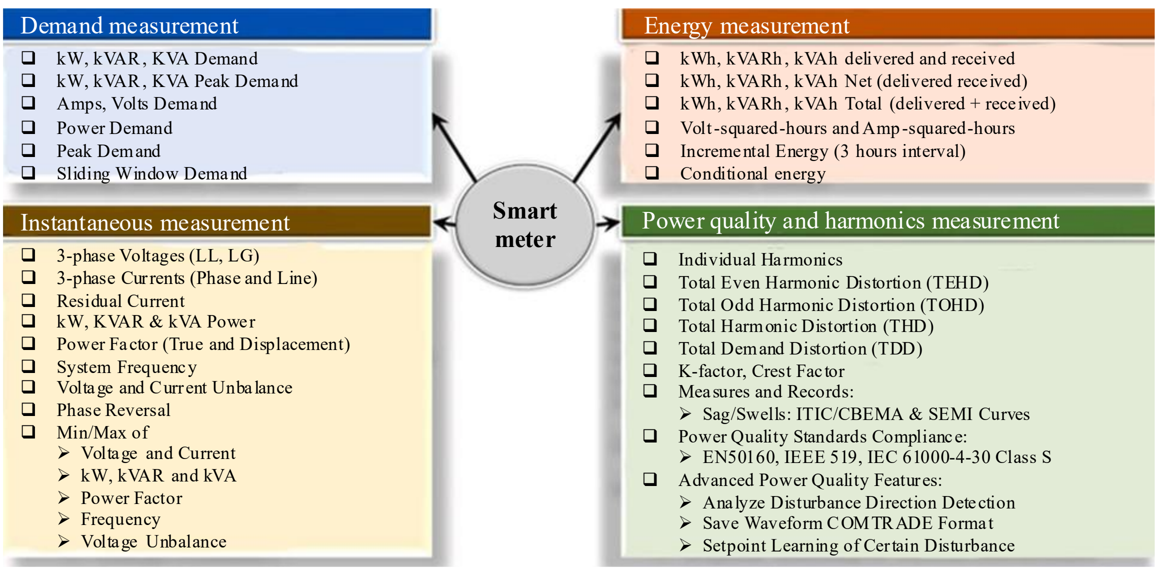

Figure 2. Application area of the advanced SM [9].

Table 1. Literature summary on SM adoption in the power distribution sector.

S.N.	Objective	Findings	Methodology	Scope
1	Secure smart meters	SMs provide security and resilience, critical for preventing electricity theft.	A secure and resilient smart energy meter.	Reducing power theft in Indian distribution networks.
2	Theft detection	Deep-CNN approaches for theft detection using SM data.	a comprehensive review and synthesis of existing research on SMs.	Applicable for combating electricity theft in India's distribution system.
3	Demand-side management	Integration of delta-sigma modulation (DSM) and net metering helps optimize energy use.	The study employs a hybrid deep neural network model combined with intelligent antenna-based SMs to detect electricity theft, leveraging advanced machine learning techniques.	Helps in balancing peak loads and managing energy consumption in India.
4	Smart meter technologies for peak load management	SMs enable efficient energy management in households and organizations, leading to peak load reduction.	The study conducts a detailed analysis and evaluation of various SM technologies, exploring their functionalities and implementation strategies.	Important for reducing peak demand in India's urban areas.
5	Consumer behavior analysis using SM data	User behavior models assist in forecasting electricity consumption.	The study develops and applies user behavior models leveraging smart metering data to forecast residential electricity consumption, employing data-driven techniques for pattern recognition and predictive analysis.	Improves accuracy in consumption forecasting, supporting efficient grid management in India.
6	Changes in energy profiles post-COVID-19	SM data revealed significant changes in energy use profiles before, during, and after COVID-19 lockdowns.	The study conducts a comprehensive review of distribution network applications, emphasizing the use of SM data analytics to enhance grid management, operational efficiency, and decision-making processes.	Useful for understanding dynamic consumer energy use patterns in India.
7	Cybersecurity and privacy in SMs	Proposed schemes to protect consumer privacy and prevent cyber intrusions in the advanced metering infrastructure.	proposes a privacy protection scheme to safeguard end-user data from cyber intrusions in smart grid advanced metering infrastructure, employing cryptographic techniques.	Ensuring consumer data privacy in India's AMI (Advanced Metering Infrastructure).
8	Power quality analysis using SMs	Implementation of SMs capable of power quality analysis for ensuring grid stability.	The study designs and implements a smart energy meter integrated with IoT technology, conducting power quality analysis.	Crucial for improving power quality in India's rapidly expanding distribution network.
9	Grid optimization using SM data	SM data can be used for control and optimization of power grids.	The study reviews existing research on leveraging SM data for power grid control and optimization, analyzing methodologies, algorithms, and applications.	Enhances grid resilience and operational efficiency in India's power infrastructure.
10	Cybersecurity analysis of SMs	Security analysis for preventing unauthorized access to SM data.	The study develops a distributed approach for the quickest detection of cyber-attacks in smart grids, employing statistical analysis and real-time monitoring techniques.	Ensures secure communication in India's smart metering systems.

SMART METER USES FOR THE ELECTRIC GRID

The advanced features of SMs provide several advantages for intelligent control and monitoring of power systems. Much of the existing research focuses on demand-side management, using power consumption data to generate consumption patterns that help consumers understand their usage behavior. However, in the context of smart grids, SMs are also used for tasks such as energy malfunction identification, electrical energy outage management, and fault location identification [14–16]. In addition, SMs are used to assess power quality issues by identifying and rectifying their sources. This section highlights some of the most common applications of SMs, as illustrated in Figure 3.

- AMI-based power theft recognition techniques
- Energy demand load scheduling
- Forecasting of load demand
- Electrical supply outage management
- Fault identification

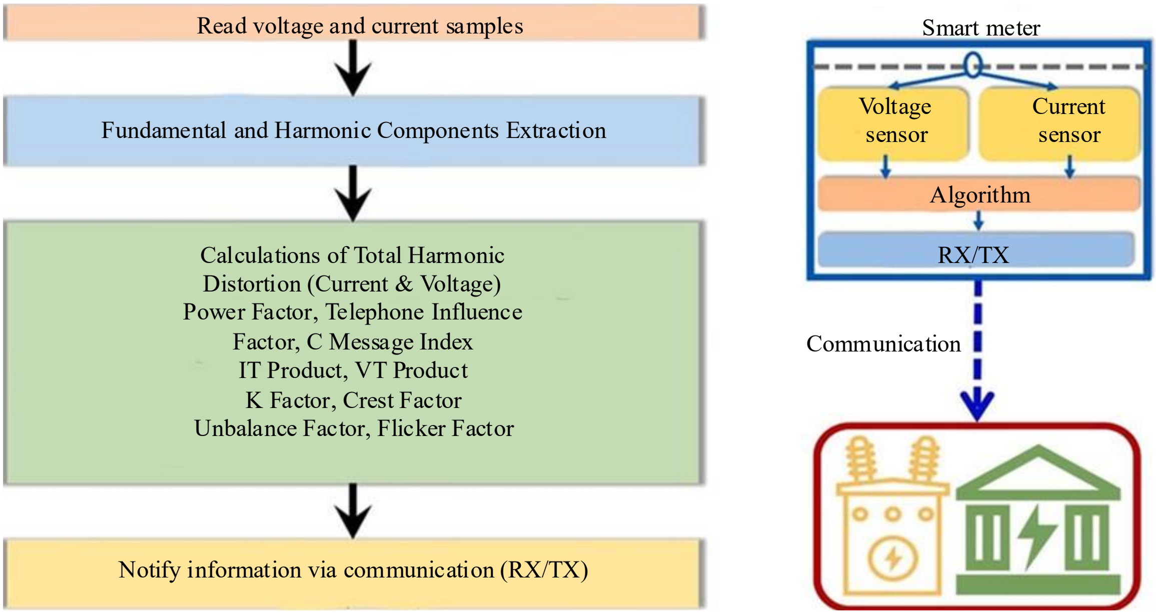

Figure 3. Implementation of SM in the power system [10].

CONCLUSION

The adoption of SMs in India's power distribution sector can enhance overall performance by improving energy monitoring, theft detection, demand-side management, and grid optimization. Addressing challenges, such as cybersecurity and consumer privacy, is crucial for fostering widespread adoption. With continued advancements in SM technologies, India's power grid can become more resilient, efficient, and capable of meeting the growing energy demand of its population.

This review illustrates the pivotal role that SMs can play in enhancing India's power distribution sector. Integrating these devices can lead to better monitoring, demand management, theft detection, and cybersecurity, all of which are essential for modernizing India's power infrastructure.

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