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IoT-enabled Smart Grid via SM: An Overview

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Abstract— Power quality and reliability issues are big challenges to both service provider and consumers in conventional power grids. The ongoing technological advancements in the Internet of Things (IoT) era provide better solutions to enhance the management of these challenges and enforce the measures of a Smart Grid (SG). Advanced Metering Infrastructure (AMI) and Smart Metering (SM) technologies are enabler technologies that can modernize the conventional power grid through exposing the hidden details of electrical power by introducing two-way communication scheme during power transaction process between utilities and consumers. Throughout literature, AMI and SM technologies are widely discussed. However, few studies discuss the role of SM in power quality and reliability monitoring in IoT-enabled SGs. Hence, the paper aims to comprehensively review the feasibility of employing SM for power quality and reliability monitoring. First, we provide a detailed overview about the SMs, wireless communication technologies, and routing algorithms as enabling technologies in AMI. Then, we categorize the existing literature works that target power quality and reliability monitoring. Finally, open research issues are outlined based on shortages in the existing literature.

Index Terms* — *IoT; Smart grid; Smart metering; Power quality; Power reliability; AMI.

I. INTRODUCTION

Electrical power is one of the essential factors for the development of societies by improving life quality. However, the conditions in power industry are changing as electricity demand and renewable integration increase. The increased stress on power demand has produced a burden on the conventional power production resources. With the noticeable decline in conventional power resources reserves and the recent attention on environmental issues associated with producing power from fossil fuel based resources, Power utilities and investors are motivated to invest into other sustainable ways of power production in order to meet the demand. For instance, one aim of the European 20/20/20 strategy is to increase the share of renewable energy generation up to 20% by 2020 [1]. Renewable resources are intermittent by nature. The increased penetration of those non-dispatchable energy sources into the existing power grid makes it more challenging for utilities to deliver reliable and good quality power. Fortunately, with the recent technological advancements, IoT inspired applications can offer great solutions to the aforementioned challenges by providing two-way communication schemes which can help in transforming conventional power grids into modernized SGs. In fact, the IoT paradigm is an essential segment of the modern SGs, especially in residential and commercial buildings' applications [2]. The smart cities paradigm is also another demanding project for IoT-enabled SGs [3]. Both of these emerging paradigms, imply that there will be a noticeable increase in the usage of sensor networks for providing useful data that enable the efficient control and management of cities [3], [4]. The concept of smart cities will not only focus on specific services such as traffic control but will also extend its means to the electric system. In fact, the usage of sensory devices and SMs in SGs ultimately solves most of electrical industry problems [1], [5], [6]. In this way, the SG will be able to effectively deal with many aspects of power generation, transmission, and distribution issues. In addition, it will provide better options for monitoring the status of power delivered to consumers. SMs provide a powerful way of enhancing power transaction process between the source and sink in a SG. The functionalities of SMs in SGs vary depending on the application objective such as energy demand saving, feedback to consumers, dynamic pricing and appliances control depending on demand curves, security enhancement, outage management, supply quality assessment [7], [8], and demand response management schemes [9]. Hence, the SG is the ultimate solution to most of the challenges in current power grids. In fact, statistical studies show that the component failures in a power system can cause more than 80% of the electricity outages/cuts in a power distribution grid [10][11]. Hence, the SG will be able to adhere to such challenges, when it is properly planned. Taking into consideration the aforementioned remarks, this study aims to provide a comprehensive review on the role of SMs in SGs with a focus on the PQ and PR monitoring applications by comparing ongoing attempts in literature while considering the different metrics and assessment standards. Firstly, we present an overview of the AMI technology to provide an in-depth understanding of the general structure of a SG that consist of SMs, CTs, and RAs. Based on this comprehensive review, we also outline the open research issues in this field as possible future research directions.

The organization of this paper is as follows: section two reviews the related academic surveys presented in literature and outlines the contributions of this paper. The third section overviews the key enabler technologies (SMs, CTs, RAs) for achieving a successful AMI for SGs. Section four and five compare SM related literature considering different metrics in the domain of PQ and PR respectively. Sections 6 reveals the open research gaps for directing future researches, and the last section concludes the thoughts introduced in the paper with some possible future work directions. In the following, Table I provides the definitions of used abbreviations in this paper for more readability.

II. OVERVIEW OF RELATED SURVEYS

A number of attempts in literature have overviewed the usage of SMs and AMI technology in SGs. For instance, in [6], authors review the challenges and advantages of integrating

TABLE I. USED ABBREVIATIONS.

Abbreviation	Definition	Abbreviation	Definition	Abbreviation	Definition
ACO	Ant Colony Optimization	FL	Fuzzy Logic	PR	Power Reliability
ACRA	Artificial Cobweb Routing Algorithm	FPGA	Field-Programmable Gate Array	PSO	Particle Swarm Optimization
AMI	Advanced Metering Infrastructure	GA	Genetic Algorithms	QoS	Quality of Service
AMR	Automatic Meter Reading	GBR	Greedy Backpressure Routing	RA	Routing Algorithm
ANN	Artificial Neural Networks	HV	High Voltage	RPA	Recursive Pyramid Algorithm
ASAI	Average Service Availability Index	ILWT	Integer lifting Wavelet Transform	RTC	Real Time Clock
ASIDI	Average System Interruption Duration Index	IoT	Internet of Things	SAIDI	System Average Interruption Duration Index
ASIFI	Average System Interruption Frequency Index	LAN	Local Area Network	SAIFI	System Average Interruption Frequency Index
BMO	Bird Mating Optimization	LV	Low Voltage	SG	Smart Grid
CAIDI	Customer Average Interruption Duration Index	MAIFI	Momentary Average Interruption Frequency Index	SLPR	Straight-Line Path Routing
CAIFI	Customer Average Interruption Frequency Index	MAIFI_E	Momentary Average Interruption Event Frequency Index	SM	Smart Meter
CELID	Customer Experiencing Long Interruption Duration	MCU	Microcontroller	SOM	Self-Organizing Map
CEMI_n	Customer Experiencing Multiple Interruptions	MLRA	Maximum Likelihood Routing Algorithm	ST	S-Transform
CEMSMI_n	Customer Experiencing Multiple Sustained Interruption and Momentary Interruption Events Index	MV	Medium Voltage	SVM	Support Vector Machine
CT	Communication Technology	NAN	Neighborhood Area Network	THD	Total Harmonic Distortion
CTAIDI	Customer Total Average Interruption Duration Index	NDN	Named Data Networking	TTRP	Transmission Time for Remaining Path
DNRPS	Dijkstra based dynamic Neighborhood Routing Path Selection	NFMCR	Neurofuzzy-based Optimization Multi-constrained Routing	WAN	Wide Area Network
DWT	Discrete Wavelet Transform	OMS	Outage Management System	WMT	Wavelet Multiresolution
EENS	Expected Energy Not Supplied	OSPF	Open Shortest Path First	WPT	Wavelet Packet Transform
EQRP	Energy efficient and QoS-aware Routing Protocol	PDR	Packet Delivery Ratio	WSN	Wireless Sensor Network
FET	Fault and Error Tolerance	PLR	Packet Loss Rate	WT	Wavelet Transform
FFT	Fast Fourier Transform	PQ	Power Quality	WT	Wavelet Transform

SMs. Authors further discuss the status of smart metering technology back then and they believe that the main aim of SMs is to fight the basic problems which exist in power systems rather than providing a luxurious operation scheme. Similarly, in [12] authors review smart energy meters – namely electricity, heat, and gas meters – by shedding the light on various possible applications and benefits. Furthermore, authors in [13] review the rising smart meter trends including AMI and CTs at MV and LV levels. This particular review sheds light on outage management – as a part of power reliability enhancement – in which an OMS is embedded into the communication structure. In another survey [7], Gouri R. Barai et al. discuss SM, AMI, and CTs as well as the benefits and challenges when it comes to SM integration. They briefly mention the usage of SMs for PQ and PR purposes. Another review in [14], discusses the elements of a SG and smart metering. In addition, authors also discuss the status of SG development in some countries. In [15], authors provide a comprehensive framework for the SG apparatus including SMs data processing, AMI, CTs, and brief discussion on RAs, and PQ and PR. Saket Nimbargi et al. review the AMI technology and the status of SM development in various countries [16]. They also consider AMI standards and cost estimates considering Indian protocols. The work in [17] reviews the CTs used in smart meters as well as some network deployment schemes with a look at the Indian vision for communication architecture for smart metering. In [18], authors review selected SMs' functionalities with an intense focus on data analysis aspects such as complexity, collection speed, and volume of data. They also survey SOM, SVM, and FL as data analysis techniques used in SMs. In 2018, two reviews [19], [20] target different important aspects in SGs one of which [19] illustrates a communication network structure designed for energy theft identification. In addition, it summarizes the existing techniques used in literature for the same target, theft identification. Whereas reference [20] reviews the AMI technology and the communication structure for SGs in four different domains – namely, operation, transmission, distribution, and customer domains – with an in depth focus on privacy and security issues.

However, none of these attempts have comprehensively targeted RA, PQ, and PR aspects in the context of the Smart Grid (SG). These topics have been occasionally mentioned in different articles. However, no in-depth details have been provided. Table II compares the aforementioned references in relation with the contents of this work. It is clear that the RA, PQ, and PR aspects need further attention. Thus, our main intention is to provide a comprehensive review on the available literature targeting those areas. Our contributions in this work can be listed as follows:

- We aim at providing an in-depth understanding for the SM-based AMI technology in SG applications considering key enablers such as the SMs, CTs, RAs.
- We discuss significant design factors in wireless CTs as well as RAs for data processing in the AMI paradigm.
- We overview and categories the existing solutions, communication technologies, and artificial intelligence techniques that target PQ and PR assessment using AMI.
- Finally, we suggest future and potential research directions in the SGs.

TABLE II. SUMMARY OF RELATED SURVEYS.

Ref.	Year	SM	AMI	CTs	RA	PQ	PR
[20]	2018	✓	✓	✓	✗	✗	✗
[19]	2018	✓	✓	✗	✗	✗	✗
[18]	2017	✓	✓	✓	✓	✗	✗
[17]	2017	✓	✓	✓	✗	✗	✗
[16]	2017	✓	✓	✓	✗	✗	✗
[15]	2017	✓	✓	✓	✓*	✓*	✓*
[14]	2017	✓	✓*	✗	✗	✗	✗
[7]	2016	✓	✓	✓	✗	✓*	✓*
[13]	2016	✓	✓	✓	✗	✗	✓
[12]	2015	✓	✗	✓	✗	✗	✗
[6]	2011	✓	✓	✓	✓*	✗	✗

* Briefly mentioned.

III. ADVANCED METERING INFRASTRUCTURE (AMI) TECHNOLOGY

The recent vast shift towards intermittent renewable energy generations, the continuous increase in power demand, as well as the environmental issues related to conventional energy sources are all considered as challenges in conventional power systems. Further, in the conventional power system, it is difficult to have complete information on the power flow in many aspects such as power quality, reliability, energy usage at different loads etc. With that being said, new technologies can be employed in a synergetic and integrated manner modernize existing power systems and cope with the challenges. AMI offers a sustainable solution in this regard which provides a two-way communication scheme between utilities and loads (consumers) as shown in Fig.1. Data including voltage and current readings as well as demand curves will be collected from loads using SMs, then the data is transferred using AMI to clouds and then to utilities in order to process the data and manage transmission and distribution processes. Then a feedback is sent back to consumers in order to monitor their consumption patterns and check the quality of received power.

A. Smart meter internal structure

A key enabling device in the AMI is the SM, where it is installed on the consumer side for collecting real-time voltage and current data. Unlike conventional AMR where data collection is monthly, SMs provide the ability of daily data collection [16] via communication networks. Hence, SMs in SGs are beneficial not only for consumers, but also for utilities and environment. The major features of SMs, but not limited to, are listed below [7], [21]:

- Energy billing
- Electricity consumption reduction
- Consumption curves for both ends
- Net metering
- Power reliability monitoring: Outage detection
- Power Quality monitoring: Harmonics and voltage disturbances classification
- Power security monitoring: Fraud and thief detection
- Automated remote control abilities
- Remote appliance control

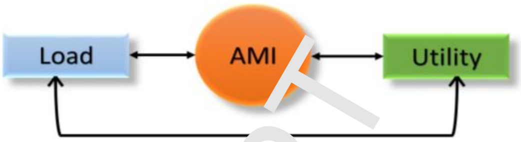

Fig. 1. General structure of AMI technology in SGs.

- Interfacing other devices
- Indirect greenhouse gases reduction as a result of reduced demand
- Less utility trucks in the streets for outage allocation and PQ tests.

The aforementioned list implies that AMI is able to deal with most of conventional power systems' challenges relative to the AMR technology. It can be said that it is expected to have more complexities in the structure of SMs since it requires integration of high-tech components to provide the good functionalities and features as illustrated in Fig. 2 [22].

SMs mainly consist of an MCU unit, a power supply unit with a complimentary battery, voltage and current sensors for active and reactive energy measurement in the energy metering IC, a RTC, and a communication facility as listed below [23]:

1) Microcontroller

MCU is the heart of a SM where most of the major data processing occurs. Therefore, all operations and functions in the SM are controlled by the MCU including the following:

- Communication with the energy metering IC
- Calculations based on the data received
- Display electrical parameters, tariff and cost of electricity
- Smartcard reading
- Tamper detection
- Data management with EEPROM
- Communication with other communication devices
- Power management.

Nowadays, most of SMs are equipped with LCD interfaces that enables the consumers to not only learn their electricity tariffs and energy consumption patterns but also learn the

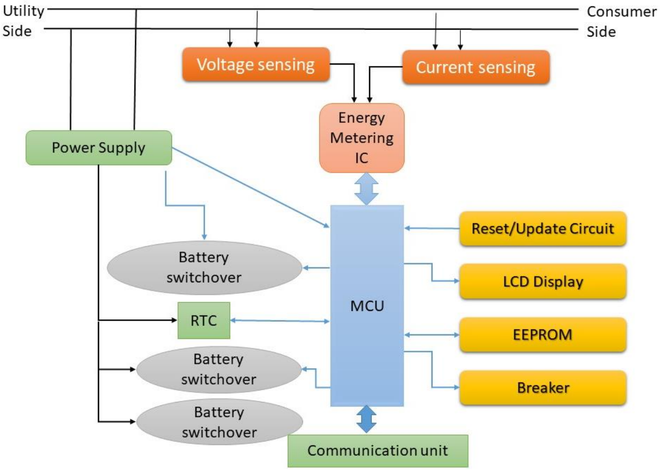

Fig. 2. SM internal design.

quality of power delivered from utilities as well as the indication of a power outage when it occurs. The MCU unit also processes such functionalities.

2) Power supply unit

The SM circuit is supplied with power from the main AC lines through AC-DC converters and voltage regulators. A supplemental switchover battery is charged from the main AC lines in order to power the circuit when the connection between main AC and power supply unit is interrupted or a power outage occurs. Solar cells and rechargeable batteries can also be used to supply SM with power during the day [24].

3) Energy measurement unit

Based on the voltage and current readings sensed by the voltage and current sensors, energy measurement units perform signal conditioning, and computation of active, reactive, and apparent powers. Energy measurement units can operate as an embedded chip into the MCU or as a standard separated chip to provide the measurements as voltage or frequency pulses.

B. Machine learning in AMI

Machine learning is another important component in AMI. Many sensors integrated in a SM are added to the smart grid for more efficient AMI implementation. The vast amount of information collected from the end-users are valuable for researchers and the smart grid operators as well. And hence, an advanced analytics on the smart grid is needed, where a combination of machine learning algorithms and data mining techniques are applied. By exploiting the emerging smart grid collected data, we can develop data-driven solutions for the most pressing issues, such as electricity demands prediction per region in a smart city, residential photovoltaic detection, electrical vehicle charging demand determination, and the time-variant load management problem.

Machine learning deals with the gather grid information in order to provide the SG the ability to learn from its history as humans. It provides information about the properties of the collected data, allowing it to make predictions about other data it may occur in the future. Generally speaking, there exist three main categories of learning in the SG, which are supervised, unsupervised, and semi-supervised learning algorithms.

1) Supervised learning algorithms

These algorithms use training data to generate a function that maps the inputs to desired outputs (also called labels). For example, in a classification problem the system looks at sample data and uses it to derive a function that maps input data into different classes. Artificial neural networks, radial basis function networks and decision trees are forms of the supervised learning.

2) Unsupervised learning algorithms

This set of algorithms work without previously labeled data. The main purpose of these algorithms is to find the common patterns in previously unseen data. Clustering is the most popular form of unsupervised learning. Hidden Markov models and self-organizing maps are other forms of Unsupervised Learning.

3) Semi-supervised learning algorithms

As the name indicates, these algorithms combine labeled and unlabeled data to generate an appropriate mapping function or classifier. Several studies have proven that using a combination of supervised and unsupervised techniques instead of a single type can lead to much better results.

C. Wireless communication in AMI

Data communication in AMI is an essential part where data are instantly collected, transferred to the utility to process it, and then utilities send a feedback to consumers accordingly. A SG covers a large geographical area, and hence the communication structure is clustered into regions in order to assure QoS in data transfer. Communication areas can be divided into three main regions as given in reference [25]. The first is LAN which describe the communication scheme between consumers and SMs. Secondly is the NAN region which basically represents communication medium that contains flowgates to perform specific processes (such as data aggregation, encoding) on the data coming from SMs before it is transmitted to the cloud. The third region is WAN which is responsible to communicate data between the cloud and destination (Utility). Fig. 3. Illustrates the communication structure in SGs.

However, there are specific areas that needs further considerations in AMI communication. In AMI infrastructure, big data transmission, data security, network scalability, and cost effectiveness are among the essential areas that needs more attention [21]. Thus, there is a need for international standards and regulations to put a framework on communication aspects in AMI. In this regard there are various standards developed by international institutions such as IEEE 802.15.4, IEC 61970, ISO 1802 [26] in order to insure reliable, secure, and efficient power delivery to the consumers. By analyzing the literature, there have been variety of communication protocols developed [27][28] according to international standards that can be used in LAN, NAN, and WAN regions of the AMI in SGs. The most common used wireless communication protocols in AMI are summarized as follows.

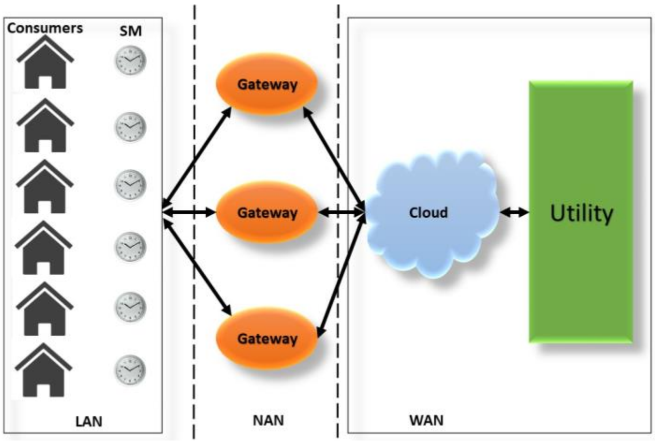

Fig 3. A review of the categorized communication technologies in SGs.

1) Local Area Network (LAN)

a) Zigbee

Zigbee is a communication technology developed according to the IEEE 802.15.4 standard that transmits data at a rate of approximately 250Kbps on 2.4 GHz frequency [29]. The technology targets applications that require short range of communication, 0-100m. Despite the short range of coverage, Zigbee proves itself in its low power consumption characteristic as well as system scalability at the cost of data transmission rate. Hence, this technology can show a good performance in the LAN region of a SG.

b) Wi-Fi

Wireless Fidelity (Wi-Fi) is another communication technology that is largely used nowadays in homes and business areas. It is designed according to IEEE 802.11b/g/n standard with a capability of data transmission at frequencies 2.4 and 5 GHz in the domain of 0-250m at a rate of 54 Mbps [30]. The domain of Wi-Fi is larger compared to Zigbee. It also provides a relatively higher rate of data transmission at the cost of scalability. Wi-Fi technology is mainly integrated into the SG system as an in-home networking scheme inside the aforementioned LAN area. This is due to its security advantage since it has a robust authentication/access procedure.

c) Bluetooth

Bluetooth is another technology that can be used for in-home networking in the SG system since it has a limited low energy communication range of (0-100m). This technology is developed according to IEEE 802.15.1 standard to transfer data at a rate of 721 Kbps [31] and a frequency of 2.4 GHz. Bluetooth is distinguished by its low power consumption and thus, it has a limited capability of vast data transfer. The widespread of the technology among users especially in smartphones gives it another advantage to be integrated in SG LANs. In addition, it's ideal for connecting the LAN of the in-home appliances with the SM.

d) Z-wave

The Z-wave technology is a radio frequency based communication is mainly designed for in-home appliances remote control which relies on an unlicensed 900 MHz frequency which transmits data at a rate reaches 40 kbps for a range of 0-30m [32]. The operating frequency of this technology reduces the risk of being disrupted by the previously mentioned technologies since they operate on 2.4 GHz frequency, which enhances the reliability of this technology. Since the data transmission speed is concern in the SG, this Z-wave technology is tested and proved to have low delay rates (in milliseconds) even with congestion that can reach 1000 simultaneous client's requests in the LAN/HAN network [33].

e) NFC

Near Field Communication (NFC) is a set of short-range protocols working at the range of about 10 cm and its targets can be simple devices such as stickers, cards, or unpowered tags attached to the SM in an AMI [103]. In addition, NFC allows peer to peer communication as well in which both devices should be powered. It can be utilized in realizing an electronic verification of the utility permits which in turn allows providing better services to citizens. It provides low-power and low-cost wireless connectivity within short ranges of up to 20 m which makes it suitable for use in Wireless Sensor Networks (WSNs), M2M and IoT-enabled SG.

2) Neighborhood and Wide Area Networks (NAN and WAN)

a) NB-IoT

The NB-IoT technology plays an important role in the AMI of a SG. The technology consists of 2G, 3G, and 4G cellular modes that provide the capability big data transmission that rates from 14.4 kbps (for 2G) until 100 Mbps (for 4G) at a licensed frequency band (824 MHz and 1900 MHz) [34]. The technology targets a large area because of its long domain that ranges between 10 – 100 km. With that being said, NB-IoT technology consumes high power for the transmission process.

b) Sigfox

Sigfox is a developing machine to machine WAN communication solution that operates on a frequency band of 868 MHz that has the ability to cover 30-50 km in rural areas and 3-10 km in urban areas to deliver the data at a rate of 100 bps [36]. An advantage with this technology is noticeable in its low power consumption for data transmission. The limitation of Wi-Fi technology to be applied in NAN or WAN is the short range of coverage. In contrary, NB-IoT provided a solution for big data transmission in WANs at the cost of power consumption. Hence, Sigfox seems to provide a middle-way solution considering range of coverage and power consumption in comparison with NB-IoT.

c) LoRaWAN

LoRaWAN is a recent non-profitable organization that is mainly established to be integrated in Internet of Things (IoT) WAN applications. The technology operates at 900 MHz frequency to transmit data at rate of 50 kbps for a distance ranges between 10-15 km in rural areas and 2-5 km in urban areas [37]. Relative to Sigfox technology considering the tradeoff between coverage and power consumption, LoRaWAN offers a better data transmission rate with reduced power consumption. Table II illustrates a summary of communication technologies used in LAN, NAN and WAN areas of a SG.

d) Wi-SUN

This communication technology is developed in line with the IEEE 802.15.4g standard in which it operates at low frequency of 900 MHz to transmit the collected data at a rate of 300 Kbps for an area domain of approximately 500 m – 5 km [35]. Wi-SUN provides a higher data transmission rate in comparison to

TABLE III. CATEGORIZATION OF THE COMMUNICATION TECHNOLOGIES IN AN AMI.

Application in SGs	Technology	Data rate	Coverage	Frequency	Standard
LAN	Zigbee	250 kbps	0-100 m	2.4 GHz	IEEE 802.15.4
	Wi-Fi	54 Mbps	0-250 m	2.4 and 5 GHz	IEEE 802.11b/g/n
	Bluetooth	721 kbps	0-100 m	2.4 GHz	IEEE 802.15.1
	Z-wave	40 kbps	0-30 m	900 MHz	ITU-T G. 9959
NAN & WAN	NB-IoT	14.4 kbps (2G) 100 Mbps (4G)	10-100 km	824 MHz and 1900 MHz	GSM/GPRS/EDGE, (2G), UMTS/HSPA (3G), LTE (4G)
	Wi-SUN	300 kbps	500 m - 5 km	900 GHz	IEEE 802.15.4g
	Sigfox	100 bps	30-50 km (Rural) 3-10 km (Urban)	868 MHz	Sigfox
	LoRaWAN	50 kbps	10-15 km (Rural) 2-5 km (Urban)	900 MHz	LoRaWAN
	LoRa modulation	0.3 - 37.5 kbps	10-15 km (Rural) 3-5 km (Urban)	900 MHz	LoRa modulation

LoRaWAN and NB-IoT 2G technologies. The usefulness of this technology is seen in low latency communications that makes it a good choice for SG NAN/WAN applications where simultaneous data processing is required.

e) LoRa

LoRa is a physical layer in Low Power Wide Area Network (LPWAN) solution designed by Semtech Corporation which manufactures the chipsets as well [102]. LoRa technology contains two main components. One of them is the LoRaWAN network protocol which has been aforementioned and is optimized for energy-limited end-devices [102]. The other one is *LoRa modulation* which is based on chirp spread spectrum technique that utilizes wideband linear frequency modulated pulses in which the frequency increases or decreases according to the encoded information [102]. In addition, *LoRa modulation* consists of a variable cyclic error correction scheme which enhances the performance of the system by adding some redundancy [102]. The coverage range of LoRa is 10-15 km in rural areas and 3-5 km in urban areas. Moreover, in terms of data rates, LoRa has a data rate between 0.3 and 37.5 kbps [102].

D. Routing algorithms

One of the essential SG characteristics that differ from conventional power grids is communication network. The new setup of communication networks in SGs should be distinguished by their ability to support time-sensitive and data-intensive management tasks [38]. For instance, the closer SMs to the gateways, the more information they will transfer which leads to more data concentration which may affect the transmission reliability. Therefore, choosing the appropriate routing algorithm is an essential area to be covered in SG communication network setups [39]. Data routing is moving one data unit through one possible communication path or more from the source to the destination node [40]. Having multiple paths to transmit the data unit from the source to the destination increases the network robustness relative to one single path in which there is a higher possibility for the path to fail. Therefore, a robust routing scheme implies adding more data transmission complexity. Since there may be multiple paths for data transmission in SG communication networks, a routing algorithm decides on which path the data will follow considering different metrics. It can be said that reliability, cost, computational power, delay, and data throughput are some of the key objectives when developing a routing algorithm [41] for SG applications. The following discusses major RA design objectives.

a) Delay

In SG communication networks if the transmitted information from the source to the destination is received late, undesired events might happen even though the data control devices take a correct action [42]. Therefore, minimizing delays in the communication network is essential to enhance the quality of data delivery. Route selection is the essence of limiting the delay in SG communication networks. Authors in [42] estimate the delay and propose the minimum end-to-end delay multicast tree routing algorithm to select the path with least delay in NAN region of SGs. Another routing algorithm is developed in [43] to ensure an efficient communication path selection for SG applications in the NAN communication region. The DNRPS algorithm shows its superiority in the reduced communication delay by a highest gain percentage reduction of 19% over other selected algorithms and Dijkstra is one of them. Delay is also studied in [44] where authors employ the ACRA to enhance the QoS of the network by focusing on the delay and data throughput for applications in low voltage power distribution networks, in this context, LAN region. Moreover, study [45] proposes routing algorithm for QoS enhancement considering delay, memory utilization, packet delivery ratio, and throughput using EQRP algorithm that is inspired by BMO. Furthermore, authors in [46] attempt to study the delay for SG applications using Greedy QoS Routing Algorithm. Whereas in reference [47] the SLPR Algorithm is used. Delay in some works [48]–[50] referred to as latency.

TABLE III
CATEGORIZATION OF ROUTING ALGORITHMS ACCORDING TO OBJECTIVES IN SG AMI.

Ref.	**Objective**								
	Delay	Lifetime	Cost	Reliability			Scalability	Coverage	Security
				PDR	PLR	FET			
[42][43][46][47]	✓							✓	
[44] [50]	✓						✓		✓
[45]	✓			✓			✓	✓	
[48]	✓	✓		✓					✓
[49]	✓				✓			✓	
[51] [52]		✓					✓		✓
[53] [56]			✓					✓	
[54] [55]			✓			✓			
[59]						✓		✓	✓
[61]				✓	✓				
[62]		✓					✓		✓

Reference [48] employs the layered cooperative processing algorithm to enhance the QoS based on latency and reliability for SG application. Whereas in reference [49] the latency and reliability are objectives enhanced using an ACO Algorithm for the application in NAN region. Moreover, in reference [50] authors used the GBR algorithm to study latency as well as throughput. Following the analysis on this literature, various algorithms are used for different application regions in the SG (LAN, NAN, or WAN) and some studies target the SG in general.

b) Security

Smart meters autonomously collect massive amounts of data and transfer it to the utility company, consumer, and service providers. This data includes private consumer information that might be used to infer consumer's activities, devices being used, and times when the home is vacant. Moreover, the smart grid has several intelligent devices that are involved in managing both the electricity supply and network demand. These intelligent devices may act as attack entry points into the network. Unlike the traditional power system, smart grid network includes many components and most of them are out of the utility's premises. This fact increases the number of insecure physical locations and makes them vulnerable to physical access. Unfortunately, there are outdated equipment which are still in service and coexist with the grid. This equipment might act as weak security points and might very well be incompatible with the current power system devices. In addition, having many stakeholders might give raise to a very dangerous kind of attack called, the insider attacks. Accordingly, a careful attention shall be paid to security issues in the smart grid before being realized in practice.

c) Coverage

Wireless connectivity is a cost effective solution to modernize the electrical grid turning it into a smart grid system. Deploying a wireless communication system is easier for consumers than installing wired communication meters. Wireless allows two-way digital communications by adding computer intelligence and data communications to the electricity distribution networks from non-renewable (coal and nuclear) and renewable energy (solar and wind) to smart appliances to plug-in cars. Key components that enable smart grid to provide two-way wireless controls and communications are smart (wireless) meters, backhaul network, utility pole radios, central utility center, and the remote sub-stations. Technical specifications and bandwidth capacity per component in the above communication system specifies the coverage region of the smart grid. And hence, the more powerful components we have, the more coverage we can gain. In general, the key characteristics that influence overall coverage range of a smart grid can be listed and quantified using Friis transmission formula as follows: 1) Transmission RF power, 2) Antenna gain on transmitter and receiver, Frequency band which can varies from 700 MHz to 5.85 GHz, Receiver Power sensitivity, and the Path Loss effect.

d) Scalability

Scalability is a central issue in the development and deployment of a smart grid system. The scalability footprint of a smart grid solution can be defined by two core criteria, load and complexity. Load is the more poignant factor, in order to isolate it, complexity has to be minimized if possible. Load scalability encompasses memory, communication and CPU loads. It is suggested to implement a smart grid with a hierarchical based structure in order to ease/relax the scalability issues. Where better communication alternatives can be utilized unlike the meshed structure for example. Because scalability is a central player for the grid performance, it is important to examine how the different grid architectures resist its influence as the system consumers increase. To prevent distorting the structure of these architectures, the increased grid scale can be achieved through the injection of additional smart meters. Smart meters quantities shall be divided equally among the demand clusters in the served region for better load balance and fair solutions.

e) Firmware updates

Security in IoT can easily get broken and the connected things including SMs can get hacked, especially if there are lots of them. For that reason, it is of utmost importance that these devices must be able to upgrade over the air (OTA). Moreover, OTA updates can significantly increase the SG scalability and deployment reliability. For example, when something goes wrong, a new firmware image (the embedded software which controls the thing) can be sent over a wireless connection to replace the broken/nonfunctioning firmware. Doing it wirelessly, removes the need for a man power to be sent out, which can dramatically slow down the service. Especially, if we are talking about upgrading millions of these SMs.

Meanwhile, upgrading a SM would be easy, if it has a high speed wireless connection. However, SMs typically send a few hundred bytes of data to the Cloud and rarely need any data to be sent back. And hence, current SG networks are optimized for data being sent from meters, not to them, which forms another challenge in upgrading any SM as they are not designed to send firmware update files to millions of meters at the same time.

f) Lifetime

SMs in the communication network of a SG are scalable, flexible, and intelligent nodes. However, these sensor nodes are subject to failure due to their limited energy capacities in which shortens the overall network lifetime. For this, authors in [51] propose an energy routing based WSN scheme to lengthen the network lifetime considering the sensor node energy limits for applications in power distribution networks whereas in [52] authors show the advantage of using MLRA over random method for extending the lifetime of SG wireless network.

g) Cost

Routing cost is another important objective that is essential when designing a routing algorithm. It is proposed in [53] that relying on OSPF technique can help reduce the cost of route selection for applications in LANs of SGs. Unlike reference [54] where authors rely on FL, namely NFMCR algorithm, for cost and error reduction in route selection for application in SGs. Cost alongside fault tolerance is also studied in reference [55] where authors employ the Dijkstra shortest path routing algorithm considering all SG communication regions, LAN, NAN, and WAN. In Another study [56], authors also employ the Dijkstra's shortest path routing algorithm to find the least routing cost among the network nodes putting the security of the grid into consideration.

h) Reliability

Reliability in communication network has something to deal with failures when transmitting information from the source to the destination [57]. From the hardware point of view, reliability can be enhanced through the inclusion of more links and components to overtake the work of faulty components in the failure situation [58] which increases the complexity and installation costs. Hence, a reliable communication network is fault/failure and error tolerant, FET. Some studies attempt to improve network reliability considering error reduction [54], fault tolerance [55], or failure probability [59]. Whereas some other studies also examine the PDR as an indicator of reliable communication. PDR is the ratio between the amount of data packets sent by a source and data packets received at the destination [60]. In SG domain, PDR is improved in study [45] using EQRP as mentioned previously. Moreover, the reliability of the link between two nodes in reference [48] is assessed using PDR and Reliability Routing Decision Algorithm is used to select the reliable routing path. Similar to PRD, In reference [49] authors attempt to reduce PLR using an Improved ACO for applications in SG NAN regions. Furthermore, both PDR and PLR are considered in [61] for applications in NAN using Hybrid Metric algorithm. Based on literature, it can be concluded that reliability enhancement is essential and should be studied in SG LAN networks since data congestion is higher on SMs around gateways. In the following, Table III summarizes related studies based on their design objectives.

IV. SMART METERS AND POWER QUALITY

Power quality simply means delivering a smooth and a steady voltage waveform to consumers. PQ issues are majorly found in variant voltage waveforms and supply frequency. These waveform disturbances accompanied with current and voltage distortions can be caused by changeable load patterns [63]. Hence, it is essential for utilities to detect and classify those disturbances, as it will enhance the power grid performance. Using SMs in assessing PQ is an important switching point as it implies the application of SGs measures. In the following subsections, we overview the literature works that target the employment of SMs into PQ assessment.

A. Assessment parameters

The global importance of PQ assessment in power distribution networks [64]–[66] brought a great attention to standardizing PQ guidelines in order to promote its assessment accuracy. Many organizations successfully introduced international standards for PQ assessment. Institute of Electrical and Electronics Engineers (IEEE) [67], and the International Electro-technical Commission (IEC) [68] are among the reputable organizations that significantly contributed in developing PQ standards. For instance, IEEE

TABLE IV
STUDIES CATEGORIZATION ACCORDING TO USED ASSESSMENT PARAMETERS

Ref.	Parameters										
	Transients	Sags	Swells	Under/over voltage	Voltage Unbalance	Voltage interruptions	Dips	Power frequency	Flicker	Reactive power	Harmonics
[77]			✓			✓	✓				✓
[78]	✓							✓			✓
[79]					✓						✓
[80]				✓							
[81]	✓	✓	✓			✓			✓		✓
[85]										✓	
[100]											✓

519-1992 is an IEEE recommended practice for harmonics control in electrical power systems that intendeds to provide steady-state operation limits in order to minimize harmonics and transients [69]. This practice is widely adopted by North American power utilities [70]. Subsequently, the IEEE 1159 - 1995 emerged aiming to build a guideline for acceptable methods of monitoring PQ in power distribution networks [71]. In addition, it classifies the typical characteristics of electromagnetic phenomena parameters that mainly causes PQ. Two standards (IEC 61000-4-7 and IEC 61000-4-15) developed by the IEC already exist [72] in which they included power quality parameters along with their calculations and interpretation methods. Further developments continued to introduce the of IEC 61000-4-30 standard [73]. Furthermore, EN50160 is a European power quality standard that is adopted by many European countries [74]. It is essential to consider standardized parameters while assessing PQ. The common parameters introduced by international standards are used in this paper for the comparison to draw a clearer picture of what mostly causes poor power quality.

Technological advancements are essential for PQ assessment [75] as it needs capable devices and instruments and algorithms to achieve accurate monitoring that meets the required standards and regulations [75], [76]. AMI technology plays an important role in this regard. Authors in [77] attempt to develop a SM network for electrical installation monitor for PQ assessment parameters including power factor, THD, and voltage dips, swells and interruptions. Authors consider an in situ big data processing capability relying on an FPGA embedded in the SM. Unlike [78] where they introduce a PQ assessment SM putting cost of measurement device into consideration. They use voltage transient detection, current drop patterns, and arc-fault detection as their evaluation parameters. In [79] voltage distortion and imbalance were used to evaluate PQ and provide an advanced warning of PQ problems as well as free data processing capability. Furthermore, a smart monitoring system is proposed in [80] that relies on voltage deficiency indications to reduce customer complaints and operational costs. In [81] authors consider reduction of computational effort for PQ disturbances classification such as sags, swells, flickers, Harmonic Distortion (HD), voltage interruptions, and oscillatory transients. That is to say, studies can be categorized according to the parameter(s) used in their assessment criteria as shown in Table IV.

TABLE V
TECHNIQUES EMBEDDED IN SMS FOR DIFFERENT APPLICATIONS AND OBJECTIVES.

Technique		Application(s)	Objective	Ref.
WT	DWT	Reactive power	computational effort	[85]
	RPA - DWT	Reactive power	computational effort	[78]
	WMT	Voltage transients	Low device cost	[86]
	ILWT	Harmonics and disturbances	-	[87]
FFT		Harmonics	computational effort	[80]
		Harmonics	Fast performance	[90]

B. Techniques embedded in SM for PQ analysis

PQ disturbances' classification and detection has been an important topic that many researchers continuously attempt to solve [81]. Various methods have been introduced in the literature to efficiently provide the status of disturbances in a power system. Regardless of using SMs in power quality assessment, the commonly used techniques are based on either, signal processing techniques (FFT, WT, ST, etc.), or artificial intelligence approaches (ANN, FL, and SVM), or heuristic optimization approaches (PSO, GA, etc.) [81]–[83]. However, these techniques and studies presented in the literature focus on PQ assessment in the context of conventional power grid. In other words, with the emergency of SGs definitions and measures accompanied with the numerous deployments of SM's, PQ analysis techniques should shift towards smart ways of implementation. A key factor of achieving the smartness of PQ analysis can be introducing in SMs-embedded analysis techniques. Undoubtedly, this will enable having SMs with multi-functionalities alongside PQ assessment such as load profile monitoring, energy billing, outage detection, or even remote automated switch control in SGs. In this context and based on the limited literature related, two techniques are revealed and compared below.

1) Wavelet Transform (WT)

The WT is mathematical model that plays an important role in signal analysis for the purpose of PQ assessment as it provides the ability to analyze waveforms characteristics in time-frequency domain [83]. The WT is useful when voltage transients as well as short-duration voltage variations (sags, swells, interruptions) are considered in the PQ studies [84]. In the light of techniques embedded in SM's for PQ studies, it is worth mentioning selected studies. For instance, In [85] the author employs the DWT to measure reactive energy with the presence of time variant PQ disturbances like voltage swells and harmonics for the objective of maintaining a less computational effort relative to WPT. Where in [78], a WMT approach is used to detect voltage transients and current drops as well as a THD measurement Goertzel algorithm considering low smart meter cost. A developed technique relying on employing the RPA in applying DWT was introduced in reference [86] where the primary aim is showing the computational efficiency of the proposed model over the normal DWT. Following an analysis presented in [87], a novel ILWT technique is employed with SMs to achieve real time compression and transmission of signals for the purpose of analyzing harmonics and PQ short duration disturbances such as sags, swells, voltage transients and interruptions, and flickers.

Following The analysis on literature, it can be said that the main advantage of using WT is observed in its ability to provide a good analysis resolution in the time-frequency domain and hence short duration voltage variations can be classified as mentioned previously. However, WT can induce computational burden on MCUs in SMs (The DWT is more efficient in terms of computation effort as shown in Table V) especially when better analysis performance is desired, which is a major

TABLE VI
SUMMARY OF SM BASED PR INDICES CALCULATION.

Ref.	Index(s)	Focus on SMs
[93]	SAIDI	Moderate
[95]	SAIDI	Moderate
[96]	SAIDI and EENS	High
[97]	SI and LB	High
[98]	PRI	High
[99]	ASIDI and ENS	Low

disadvantage of this technique.

2) Fast Fourier Transform (FFT)

FFT is another widely used signal analysis technique which mainly converts signals from time to frequency domain [88]. The usefulness of this transform is observed in periodical signals, namely in identifying their phases and amplitudes [89] and hence determining noticeable harmonic events. As in [32], it is used to achieve a low computational burden on the hardware while evaluating the harmonic distortion. In this study, the model is only applied on harmonics extraction and two other artificial intelligent approaches (ANN and decision trees) are used to extract short-term PQ disturbances including sags, swells, and oscillatory transients. The simplicity of implementation in FFT makes it a noticeably fast processing technique relative to other complex techniques. In [90] FFT is preferred for its fast performance and accuracy to detect and estimate THD when embedded in a SM.

One advantage of using FFT in PQ assessment alongside with SMs is that it provides fast performance and accuracy for harmonics evaluation. Another advantage is that FFT is observed to be suitable to be embedded in SMs for PQ assessment compared to other techniques [91], [90]. Nevertheless, FFT shows weak performance in terms of short-term variations detections and time-frequency domain resolution relative to WT. Table V shows the usages of both techniques embedded in SMs for different applications and objectives.

V. SMART METERS AND POWER RELIABILITY

Power reliability simply is related to the total electric interruptions in a power system that has to do with the full loss of voltage waveform unlike power quality which covers voltage sags, swells, and harmonics [91]. A highly reliable power system means that power is to the consumers all the time without any interruptions. However, power systems are not ideal and various factors can affect power system reliability, which means economic loss to both utilities and consumers. It is estimated that 80% of power reliability issues occur in the power distribution network [92]. Hence, in conventional power systems the details of interruptions and outages are hidden. With technological advancements, AMI technology and data analysis techniques are proved to enhance the exposure of power system issues and measure the severity of interruptions [93] which enhances the movement towards the concept of a SG. In the light of SMs, there have been many ways and techniques used in literature to evaluate the reliability of the delivered power from utilities to consumers. This is achieved through determining defined reliability indices. Whereas some other techniques in literature attempt to detect power outages interruptions in a power system. Various standards construct a framework for assessing power reliability in a power distribution network. IEEE1366-2012 standard is among the widely used standards that presents indices can be used in assessing power reliability [94] which presents sustained and momentary interruption indices as well as load based indices. Frequency, duration, and the extent of the interruption are essential parameters used in characterizing reliability of the power system [95]. Indices presented by IEEE1366-2012 are briefly categorized in Fig. 4. Sensors are deployed with sufficient amount in HV and MV networks, which enables the accurate monitor of power reliability events. With the introduction of AMI in LV networks, namely SMs, there is a great opportunity of enhancing the monitoring capabilities on the LV side. That is to say, reliability indices can be accurately calculated with the help of SMs at the LV sides. As done in [93], authors present a method of calculating temporospatial disaggregated reliability SAIDI index relying on SM data. In this context, SMs also provide the ability of interruption time reduction relative to conventional meters. Replacement of conventional meters with SMs in a power distribution utility in Brazil is discussed in [96] considering SAIDI index and EENS. The study shows a noticeable annual reduction of both SAIDI and EENS for the period between 2011 and 2015 where they achieved a 16.54% reduction in 2015. Unlike a study [95] implemented in Helsinki, Finland shows that the help of SMs enabled utilities to achieve a percentage reduction of 50% in SAID index. Whereas AMI technology had more focus in reference [97] which develops a Zigbee based automated reliability system that is able to calculate and display reliability indices including sustained and load based indices. Following the focus on employing SMs in calculating reliability indices, authors in [98] propose an evaluation model for Power Reliability Index (PRI) which uses the PQ data recorded by the SMs. The usefulness of this study is observed in employing both PQ and reliability considerations to enhance the overall grid system operation with an intense focus on SMs. Unlike reference [99] that briefly considers the usage of SMs in this

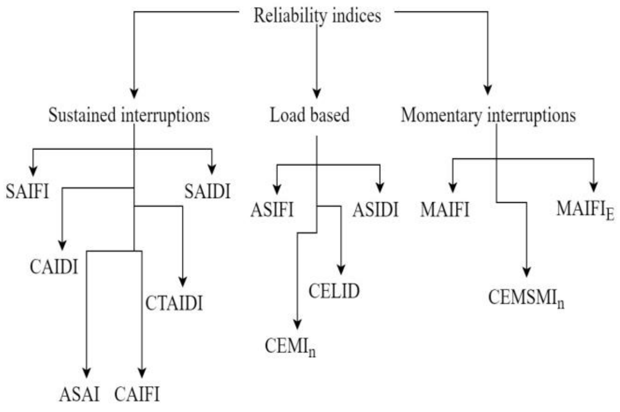

Fig. 4. Summary of IEEE1366-2012 reliability indices.

regard but attempts to calculate reliability indices such as ASIDI and ENS as an additional adjective. Following analysis on the limited literature in the domain of using SMs for PR indices calculations, applications vary in the indices calculated as well as the focus on the usage of SMs. Hence, it is essential to develop further attention on PR assessment using SMs considering either calculating PR indices or employing WSN schemes for outage detections. Table VI summarizes the studies that rely on SM data for PR indices calculation.

VI. OPEN RESEARCH ISSUES

According to analysis on previous literature in this paper, we suggest further investigations on the following issues:

1. Big data management schemes in order to reduce data congestion in LAN.
2. Multifunctional SM developments. Additional functions can include PQ and PR assessment together with the typical SM tasks.
3. Optimal reconfiguration of communication infrastructure so that it accommodates PQ and PR assessment schemes either through calculating PQ/PR indices or employing WSN for event detection.
4. Simultaneous and optimization algorithms for network reconfigurations.
5. Development of ML algorithms embedded in SMs for real-system health monitoring. Which can include various PQ and/or PR indices.
6. Development of SM-embedded techniques to detect short-time supply/demand variations.
7. PQ and PR monitoring/assessment systems development according to recognized world standard.
8. Development of efficient and accurate SM-embedded algorithms and techniques.
9. Development of synergetic integrated models that include other AMI applications alongside PQ and/or PQ monitoring.
10. The number of customers in SGs is huge and exponentially increasing. Hence scalability is an essential design parameter as to enhance the communication network reliability.
11. The massiveness of the smart grid and the increased communication capabilities make it more prone to cyber-attacks. And thus, further security-based solutions are required.
12. Practical issues with SGs like device configurations and software updates are still in need for more attention to be better realized. Over-the-air updates for example can offer various benefits such as the product behavior monitoring, increased SG scalability and deployment reliability. However, due to these issues, it is still unreliable and prone to several failures.
13. The expected future transition from conventional power grids to SGs will need topology planning in the LV side of the grid considering the range of coverage. For example, tree/cluster based sensory networks can be applied for better coverage.
14. CTs categorization enhancement based on their respective advantages and disadvantages in relation with the topology plan is also required.
15. Enhancement of CTs data processing in terms of time-sensitivity and data-intensity is significantly needed.
16. RAs enhancement in relation with the future SG communication technology is required.

VII. CONCLUSION

The importance of PQ and PR in power grids has brought an increased attention to developing new ways and techniques for their assessment. IoT is believed to provide a long-term solution to help solving such problems as well as providing the essential building blocks for enforcing the measures of SGs by employing AMI and SMs technologies. For this, we reviewed the effectiveness of employing these technologies onto conventional power grids for PQ and PR assessments. The structure of AMI and SM technologies including wireless communication technologies as well as data routing algorithms are thoroughly discussed and open research areas are suggested accordingly.

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Highlights

This paper aims to review on the effectiveness of employing the Smart-meters technologies in smart-grids with focus on power quality and reliability issues.

Existing wireless communication technologies with data routing algorithms are thoroughly discussed in the IoT era.