Wireless MEMS for smart grids

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11.1 Introduction

Different from the past, nowadays, consumers demand more flexibility and control in managing their electricity use and are aware of the impacts of the electricity system on the environment. Due to this change in the use of electricity, renewable energy sources such as solar power and wind play a key role. They not only allow consumers to generate their own electricity and sell the excess electricity they have generated, but they also help to reduce greenhouse gases. However, existing power grids primarily move electricity from generators to consumers. As a result, a paradigm shift is required regarding how the electricity system is built and operated. The paradigm shift forces electric utilities to upgrade their power grids to respond to the consumer demands by implementing advanced technologies and new methods in the production, delivery, and use of electricity. The modern power grid that emerged from this paradigm shift is called "smart grid (SG)."

A SG is the next generation power grid, which uses distributed sensors, monitoring, automation, communications, and information technology tools to improve the reliability, efficiency, flexibility, scalability, safety, and security of the overall electricity system [1–4]. SGs include diverse and distributed traditional and renewable energy resources, and they accommodate electric vehicle charging. Different from traditional power grids, SGs increase consumer choices using prices or other parameters delivered via enhanced two-way communication, thereby allow consumers to better control their electricity use [5–7]. SGs utilize different applications with different communication and quality of service (Qos) requirements; therefore, they involve heterogeneous communication technologies based on a multi-tier communication infrastructure [8–13]. In short, SGs bring all elements of the electricity system together in an efficient way so that the overall operation of the power grid is improved for the benefit of electric utilities, consumers and the environment.

In SGs, through the use of advanced sensing, sophisticated automation and complex two-way communication infrastructure, the equipment performance, power system reliability, restoration times, and power quality are improved. Also, maintenance and operations are improved with the help of enhanced system planning. Although it is highly promising, SG transformation is not risk free and the cost of implementation on a commercial scale for some of the emerging technologies involved in the transformation may be prohibitive. In addition, interoperability between existing and emerging technologies is highly challenging. Therefore, overcoming the challenges involved in the SG transformation not only require investment and hard work, but also creativity, innovation, and flexibility.

Wireless MEMS Networks and Applications. http://dx.doi.org/10.1016/B978-0-08-100449-4.00011-7

Due to the requirements of SG applications and the sophisticated infrastructure, it has been proven that the real potential of SG technologies can only be realized if the involved processes are redesigned or improved. In this respect, micro-electromechanical systems (MEMS) technology can greatly help. MEMS technology is highly versatile and has many application areas. MEMS technology allows integrating sensors, actuators, and electronics on the same silicon chip and offers many benefits to different industries in addition to reducing manufacturing costs [14–19]. Since SG applications rely on continuous real-time information from a large set of distributed sensor nodes, MEMS technology can be a valuable tool to expand and enhance the capabilities of the power grids at the same time reducing the operational and maintenance costs. In this chapter, we focus on the use of MEMS technology for SG applications in different power grid environments.

The remainder of this chapter is organized as follows. Section 11.2 presents the SG concept and explains its components and common applications, along with the communication standards used in power system environments. Potential applications of MEMS technology in power system environments, communication standards in MEMS communication, and power sources for wireless MEMS devices are discussed in Section 11.3. Research challenges with the use of wireless MEMS in a SG environment are reviewed in Section 11.4. Section 11.5 presents open research issues, and Section 11.6 concludes the chapter.

11.2 Smart grid

Basically, an SG is an information rich modern electric system. Transformation of a traditional power grid to an SG encompasses a variety of core changes in how electricity is produced, distributed, and used, and it results in a highly efficient, interactive, reliable, and scalable electricity system [1,3]. Since the SG relies on the timely delivery of information, it requires a sophisticated analytic infrastructure. It also requires trained employees and well-defined processes, since integrating and acting on gathered information in very limited time is necessary. The information provided to the SG improves power quality. SG transformations generally encompass solutions from multiple vendors and suppliers [20,21]. Hence, they must rely on open architectures characterized by clear standards with security protection.

The SG offers enhanced operational performance and better environmental friendliness, allowing the easy integration of renewable energy sources. With its sophisticated remote monitoring, automation and control systems, and novel applications, problems in the electricity system can be anticipated and addressed [2,3,5]. The ability of remotely monitoring equipment conditions and system performance enables the SG operators to realize better maintenance facilities along with accurate replacement decisions. Therefore, outages can be prevented before they occur, the scope of the outages can be minimized, sometimes called as “islanding ability,” and rapid restoration of power can be realized automatically. In this respect, the SG can be described as a self-healing power grid.

From the consumers’ point of view, SG technologies are generally seen as a revolutionary way of changing how electricity is used, because they increase the ability of the consumers to control household appliances using a number of SG applications, such as demand response, and at the same time contribute to a better environment integrating electricity generated from renewable energy sources with less carbon footprint. Not only the residential customers but also commercial and industrial consumers benefit from the SG technologies. To this end, with its enhanced communication and novel services, the SG changes how electric utilities, retailers, and consumers interact.

11.2.1 Smart grid applications

An SG automates functions that are controlled manually in traditional power grids, and in this way it increases productivity and efficiency. Moreover, it provides significant operational advantages such as real-time delivery of system information and remote control and automation of system components. On the other hand, the cost of SG implementation is very difficult to quantify. Therefore, most utilities prefer scalable implementations due to the initial deployment costs and SG expenditures. This subsection briefly explains major SG applications.

- Substation automation: Substation automation (SA) systems enable utilities to manage the flow of electricity in transmission and distribution grids. SA systems are important tools for the utilities since they protect and control substations and ensure grid stability [7]. Also, with the services of SA systems, real-time system performance of power grids can be greatly enhanced.
- Wide area situational awareness: Wide area situational awareness (WASA) systems enable electric utilities to foresee and address problems before the problems lead to outages, breakdowns, or power blackouts, minimize the scope and coverage of outages occurring, and enable rapid restoration of power by greater awareness of system conditions [20].
- Overhead transmission line monitoring: Overhead transmission line monitoring (OTLM) monitors and rates existing and new overhead lines based on real-time monitoring of conductor temperature, load and weather conditions in order to enhance the safety and flexibility of grid operations.
- Distribution automation: Distribution automation (DA) systems provide remote monitoring and control solutions for distribution and sub-transmission assets. DA systems allow individual devices to sense the operating conditions of the grid around them and make adjustments to improve the overall power flow, and this way, SG performance is optimized.
- Advanced metering infrastructure: Advanced metering infrastructure (AMI) and smart meters together enable the connection between consumers and utilities, and hence they build the first step of an information and communication infrastructure necessary for the functions of an SG. While AMI provides communication between utilities and smart meters, smart meters mainly provide data necessary for billing processes and a set of other functions including informing utilities of whether a consumer is without power or not, indicating the power and voltage quality at the consumer's meter, and permitting automatic initiation and disconnection of service [20–23].
- Home energy management: A home energy management (HEM) system enables consumers to manage their electricity use, and it brings various automation functions to their homes. In addition to a smart meter, it consists of a group of components such as an in-home energy display, a web-based tool, and smart appliances.
- Demand response: Demand response (DR) is one of the key SG applications and can be described as the ability of consumers to shape their electricity use in response to price or other signals. It provides significant benefits to utilities such as better use of distributed renewable generation sources, reduced use of highly expensive peak generation, and

reduced/eliminated need for facilities to respond to severe peak demand occurring a few times a year [20–22]. Through DR programs, consumers agreeing to slight adjustments in their electricity receive credits on their bills.

- Asset management: Asset management systems provide inventory control, property management, logistics management, and maintenance planning ability for utilities.
- Vehicle-to-grid: Plug-in electric vehicles offer lower costs and reduced emissions. But their country-wide, widespread adoption will present not only opportunities but also challenges for the SG. One of the most important challenges is how electric vehicles will be charged safely without adversely impacting distribution equipment. On the other hand, one of the most important opportunities is how the energy stored in electric vehicle batteries can be used to provide energy for peak demand. This is called vehicle-to-grid (V2G) and enables electric vehicles to become mobile energy resources [24,25].

Along with the abovementioned applications, distribution management, outage management, and meter data management are other important SG applications.

11.2.2 Communication standards and requirements

SG communication infrastructure basically caries two types of information flow [3]. While the first information flow consists of data received from sensors and electrical home appliances to be delivered to smart meters, the second information flow consists of data received from the smart meters to be delivered to the data center of the utility. The communication infrastructure to carry the first information flow can be built using a number of existing technologies such as power line communication [13], Wi-Fi, or other wireless communication standards mainly developed for wireless sensor networks such as 6LowPAN and ZigBee [5]. On the other hand, the communication infrastructure to carry the second information flow can be built using Wi-Fi, cellular communication technologies, or the Internet. Due to very high initial deployment costs, different application requirements and being spread over a very large geographical region, and heterogeneous network technologies are commonly found in SG communication networks. For instance, cellular networks provide good complementary coverage to a mesh network and give more cost effective support for isolated and hard-to-hear locales and opt-in deployments.

From the topology point of view, SG communication infrastructure can be divided into different transmission categories, namely wide area network (WAN), neighbor area network (NAN), and home area network [5]. Since different SG applications have varying degrees of requirements in terms of several parameters such as data rate, latency, reliability, robustness, QoS, and security, their requirements should be taken into account during deployment [8], and proposed communication technologies must be able to address those requirements. Although SG deployment brings many advantages to utilities, consumers and the environment, investment decisions are generally made considering many aspects, primarily costs. The following list briefly describes the parameters playing roles in the selection of SG communication technologies.

- Data rate: Building a communication infrastructure for SGs does not just mean that addressing the communication requirements of AMI is sufficient. The SG must be able to provide higher data rates and less latency for some SG applications.
- Latency: Although latency is not such a critical parameter for some SG applications such as HEM systems, some SG applications such as DA systems and WASA cannot bear high latencies since they require real-time information to function properly.

- Throughput: SG communication networks are responsible for carrying different types of traffics used by different applications. In this respect, before WAN and NAN are deployed, their overall throughput must be considered for both current applications and future applications.
- Reliability: In SGs, due to the quantity and criticality of operational data, major performance factors such as data rate, bandwidth and delay are not enough; reliability of communications technology is also important.
- Availability: The availability of timely information is the key requirement of all SG applications because the quality and availability of services to consumers and utilities depend on the availability of timely information. In this respect, SG communication infrastructure must be able to ensure high availability by providing each endpoint multiple paths in addition to automatic fail-over and self-healing capabilities.
- QoS: Although all SG applications need a reliable communication infrastructure, their data requirements and latency tolerance vary greatly. For instance, smart metering does not require much bandwidth and tolerates latency. However, DA systems require much lower latency, since quick response is critical to grid uptime. Therefore, the ability of prioritizing traffic ensures that critical data is transmitted first.
- Scalability: It is an important factor in the capacity planning process of all SG communication networks, but it is critical for WAN and NAN. While low-latency networks that provide ample bandwidth to handle multiple applications seem sufficient during the deployment, they must be scalable for future applications.
- Interoperability: As a result of SG standardization efforts, different devices produced by different manufacturers can interact over a given communications technology. Therefore, SGs must be designed with interoperability as a key requirement, since interoperability in communication networks allows a variety of communications technologies to work together, and this way, utilities can select different technologies and providers suitable for their operations.
- Manageability: Different parts of SGs require different communication technologies. Since the communication infrastructure is based on multiple communication technologies, common head-end and network management software is a must for manageability.
- Cyber Security: In addition to many opportunities, SG transformation poses risks with respect to cyber security. While SGs allow a sophisticated view and analysis of power grid operations due to the sensors, communications, and computer analytics, cyber security risks arise. During SG deployments, millions of devices are placed on poles, lines, and the sides of houses throughout a city, region, or country, and all of the placed devices need to communicate with utility computer systems.

In summary, there is not a single solution that can address the needs of all of the SG applications. Therefore, electric utilities select and combine different communication technologies to support all the aspects of the SG and enable the SG to perform different functions properly.

11.3 Wireless micro-electromechanical systems (wireless MEMS) for smart grid

MEMS devices can be described as micro-machined, physically functional devices with a number of components on the same chip depending on the proposed functions of the devices. Although the functions of devices produced using integrated circuit technology are strictly electronic, MEMS devices provide optical, mechanical, and fluidic functions as well as electronic ones [14–19,26,27].

In SGs, timely information about equipment failures, capacity limitations, and natural accidents is highly critical to ensure real-time and reliable diagnosis of possible failures proactively. This way, power blackouts can be prevented or their coverage can be minimized. This makes low-cost remote sensing ability vital for efficient, reliable, and safe power delivery in the SGs. In this respect, wireless MEMS can replace existing sensing technologies with their distinct advantages. The following sections introduce potential applications of MEMS technology in SG environments and reviews MEMS communication technologies.

11.3.1 Potential applications of MEMS technology in the SG

Power distribution environments pose several challenges to device designers such as high vibration, high temperature, electromagnetic interference, and blockage of wireless signals. On the other hand, with their unique features, MEMS devices can function reliably to provide different functions even in harsh power grid environments. For instance, ceramic MEMS technology has all the essential characteristics required for functioning properly in harsh power distribution environments [27]. As a result, as summarized in Table 11.1, MEMS sensors have been used for many applications in different parts of the electrical grid shown in Fig. 11.1. The applications of MEMS sensors in power grid environments include partial discharge detection in power transformers, partial discharge detection in high voltage cable joints, line fault indication in DC power lines, power metering, electrostatic field measurement, and high power switches.

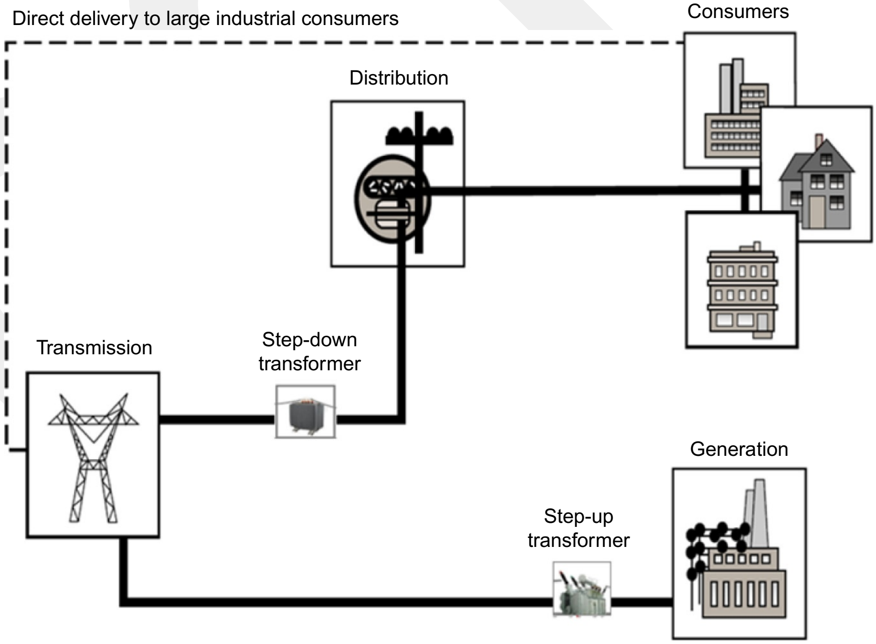

Fig. 11.1 Electrical grid from a broad point of view.

When low-cost and highly distributed sensors are installed in power transmission and distribution systems, highly detailed data regarding the operation of the grid components can be collected and can then be incorporated into the SG infrastructure. The collected information can also be used to improve the overall stability of the power grid and enhance the grid's diagnostic capabilities. In this respect, fault detection is one of the most important functions for which MEMS technology can be used. It is one of the intelligent monitoring and outage management tasks performed for the realization of self-healing networks like SGs [39]. Fault detection relies on gathering data gathered from various intelligent electronic devices installed throughout the power system and enables faults to be located in both transmission and distribution systems.

OTLM is an important application in the protection and management of power grid assets. A scheme that explains the use of fiber Bragg grating strain sensors for monitoring icing on overhead transmission lines is explained in [40]. Due to the high voltage in overhead transmission lines, powering of MEMS devices may not be practically easy. In this respect, a novel radio frequency (RF) powering system for MEMS strain sensors is presented in [41]. Inclination or the amount of line sagging must be periodically controlled since the monitoring of overhead power lines helps electric utilities provide reliable service at optimized cost. For this aim, a portable wireless MEMS inclination sensor system is presented in [42].

Energy conservation can only be realized by sensing electrical power use in commercial and residential settings. When MEMS sensor modules are installed in the commercial and residential settings in addition to power transmission and distribution systems, they can measure electrical quantities such as instantaneous power, voltage, and current. Paprotny et al. [34] proposed a MEMS sensor module for measuring electrical quantities and presented its design along with the energy harvesting module. Helistö et al. [43] designed a MEMS-based voltage detector for the same task. They proposed a new method to detect small DC and low-frequency voltages based the microelectromechanical force. Leland et al. [44–46] presented the design of a prototype MEMS sensor for AC designed for monitoring electricity use in commercial and residential environments. The sensor design proposed by Leland et al. consists of a piezoelectric MEMS cantilever with a permanent magnet mounted on the cantilever's free end.

Most of the consumers desire that emerging technologies will not be intrusive. For smart energy monitoring in houses, especially when there are old electrical home appliances, there is a need for wireless power sensors that will be simply placed over a power cord to monitor power consumption of the appliances. Pai et al. [47] report the design steps of a wireless non-intrusive power sensor with an on-board energy harvesting module that reports power consumptions to smart phones or smart home control units. In this way, the efficiency of home appliances can be monitored and their operation can be scheduled to minimize energy costs.

Portable wireless communications devices with timing and frequency control can greatly benefit from MEMS technology because the ability to shrink high-Q passives can dramatically change the premises under which wireless subsystems are designed and developed [48]. MEMS technology also offers cost and performance advantages for optical networking applications in the area of tunable lasers, variable attenuators, switching fabrics, and other devices [49].

Since all small-scale wireless devices require electric power, with the proliferation of those devices, the development of energy harvesting techniques suitable for portable and miniaturized devices has been accelerated. The harvested energy can be used as a battery substitute or can be utilized to drive the electronic devices. However, most energy harvesting sources are not reliable, and hence the harvested power varies seriously. Kim et al. [50] proposed a novel energy harvesting technique that extracts very stable power from the stray electric field around an insulated household AC power line without removing the insulation. Paprotny et al. [51] and Leland et al. [52] presented the design, modeling, and fabrication processes for MEMS AC energy harvesters that can extract up to 2 μW.

Due to the numerous benefits of SG transformation as a result of the improved intelligence of the electricity grid, such as improved energy utilization and reduced energy use and cost, there is growing interest in improving the intelligence of the vast infrastructure of power distribution cables from appliance cords, to the distribution cables, to transmission lines [53,54]. However, this requires ubiquitous, easy-to-install, inexpensive sensors with little or no maintenance requirements. To address this need, an external MEMS-based voltage sensor measures the applied operating voltage inside AC high voltage insulated power distribution cables in overhead installations, in outdoor underground power systems, and in vaults inside buildings non-conductively and transmits the measurements wirelessly is proposed [53,54]. The MEMS-based voltage sensor can be used in conjunction with MEMS-based current sensors to measure power flow in distribution cables [53,54]. The MEMS-based voltage sensor is a valuable tool for many applications, specifically for monitoring the line-to-line and/or line-to-ground voltages on insulated or uninsulated energized conductors, determining the power flow in power delivery systems and the balance in loading of the several phases of multiphase systems, and assessing the effect of temperature-induced line sag to distinguish the impact of vegetation growth on distribution cables [54]. To sum up, while potential applications of MEMS devices for SGs are not limited and there are many more emerging potential SG application scenarios, Table 11.1 describes common SG application scenarios in which MEMS devices can be used.

11.3.2 MEMS communication

Since wired communication cannot be easily and practically implemented for MEMS devices due to the size constraints, all types of wireless communication options such as RF, optics, and acoustic are preferred for MEMS devices. Among the available options for wireless communication, RF is the most popular one since data transmissions over long distances and communication frequencies in the 10 s of GHz can be achieved. Acoustics provide much lower data rates than optical and RF communications. Compared to acoustics, optical communication achieves higher data rates. While simple communication systems based on opto-electronic communication can transfer a few Mbps data over short distances, complex systems based on active optical systems can transfer much more data over long distances [26].

Table 11.1 Potential applications of MEMS devices in SG environments

Role	Reason	Advantages and disadvantages
Partial discharge detection in power transformers with acoustic emission [28]	Partial discharges deteriorate the insulation. By using at least three sensors, the location of partial discharges can be found and partial discharge harmfulness can be classified by frequency analysis [29]. MEMS-based sensors can be used for this purpose	It is an on-line method; however it is susceptible to external disturbances
Partial discharge detection in high voltage cable joints with acoustic emission [28]	Partial discharge activity may occur due to defects within polymeric insulation and cable joints [30]. MEMS-based sensors can be used for this purpose	It is an on-line method and no galvanic contact is needed; however it is susceptible to external disturbances
Line fault indicator for DC power lines	Typically, a shunt transducer is used for high-voltage DC current measurement and collected data is transmitted optically [31]. However, an MEMS magnetometer/coil magnetometer can be used for high voltage DC current measurement	An MEMS magnetometer is based on Lorenz force, is stable, and requires very infrequent recalibration and battery changes. Moreover, an MEMS coil magnetometer does not need battery changes since it harvests energy from the power line using a current clamp and communicates through radio links
MEMS-based energy harvester	While the most common type of energy harvesters is the solar cell, other types of energy harvesters, such as the ones based on temperature differences, radiation levels, and motion, may be better options where high ambient light levels are not present. For instance, for motion energy harvesting, an MEMS mechanical-to-electrical transduction mechanism at a size scale of 1 cm^3 and below can achieve [32]. Another example of an MEMS energy harvester is a non-resonant electrostatic device that can harvest up to 2.6 μW at 26 Hz [32,33]	MEMS-based energy harvesters are very small and can easily be integrated in all types of wireless sensor nodes and home electrical appliances

Continued

Table 11.1 Continued

Role	Reason	Advantages and disadvantages
Self-powered MEMS modules for power measurement	Self-powered MEMS modules can measure current and transmit calculated results with radio [34]. An MEMS component with a piezo-coated cantilever and a printed micro magnet on its tip measures current. Self-powered MEMS magnetometers can measure 50/60 Hz active power [34] as well. In these devices, current coupling is magnetic and voltage coupling is galvanic. Also, a passive, proximity-based MEMS sensor can be used for the same purpose [35]. It can be constructed of a piezoelectric cantilever with a permanent magnet mounted to the cantilever's free end [36]	Its linearity is good ($R^2 > 0.99$) and sensitivity is ~1 mV/A in a range of 0–20 A_{RMS}. It has small size, enables autonomous operation with energy harvesting from AC lines, and can be integrated into all household devices
Electrostatic field measurement	A resonating plate with a shutter moves over two sensing electrodes and the shutter blocks the electric field lines. Due to its movement, differential displacement current is generated to the electrodes [35]. A nonlinearity of 20 V/m over a range of 700 kV/m is possible, and a noise floor of 4 V/m/$\sqrt{}$Hz was reached [28]	It does not need bulky sensor electrodes [35]
High power switch	An MEMS switch is smaller and faster than a conventional relay and can handle higher power densities than a solid state switch [37]. A matrix of small switches can be realized in series and in parallel, and thus high voltages and currents can be enabled. Moreover, actuation can be electrostatic, magnetic, or pneumatic [37,38]	A single MEMS switch can have 300 V insulation strength and 400 mA current handling capability [37]

Due to customer demands for new functions, manufacturers add more and more features to the devices they produce. However, this can only be realized at the expense of more costs, but the customers at the same time expect lower costs, lower power consumption, smaller form factors, more performance, and higher reliability. One of the reasons why these wireless MEMS devices are needed is the single-chip RF circuit technique. Using the single-chip RF circuit technique, discrete components of an RF MEMS device can be replaced and the device can be integrated on the RF chip itself [17].

11.3.3 MEMS power sources

Wireless MEMS devices have very low power consumption and their energy is provided from batteries or hybrid solutions composed of batteries and micro energy harvesters. Whereas the size restrictions of wireless MEMS devices call for micro-sized batteries and energy harvesters, the power consumption of wireless MEMS devices must be as low as possible [26,27]. As a result of the low power consumption, the heat generated by MEMS devices is low and the stability is improved [55].

For long-term applications, the use of internal and/or external batteries as primary power sources for the MEMS devices either calls for periodic battery replacements [19] or requires utilizing energy harvesting solutions to increase the lifetime of wireless MEMS devices. However, periodic battery replacements require an additional maintenance expense. In contrast to outdoor environments, mains power is available in power distribution environments. On the other hand, in most power distribution environments, high voltage is easily available but low voltage is not available. Therefore, additional wiring and transformers are necessary.

Due to the form factor packaging of commercial cells, which makes the integration difficult, tape-cells are preferred in MEMS devices. While wireless MEMS devices are primarily powered by conventional electrochemical cells, microscale energy generation/harvesting solutions such as solar panels, wind turbines, vibration energy harvesters, electromagnetic energy harvesters, and thermoelectric energy harvesters can also be used. The following list briefly describes existing energy harvesting solutions that can be used in power grid environments.

- Solar energy harvesting: It converts sunlight into electricity using a photovoltaic system. Due to its characteristics and limitations, it requires energy storage elements to store the energy harvested from the photovoltaic system and to provide a stable voltage. It can be used in both outdoor and indoor environments, although the indoor energy harvesting capacity is limited. The drawback of this solution is that most photovoltaic systems are generally notorious for their low energy conversion efficiency and sunlight may not be continuously available [7]. Energy density of solar energy harvesting is around 100 $\mu W/cm^2$ at 10 W/cm^2 light density in indoor environments, and it is around 15 mW/cm^2 in outdoor environments [56,57].
- Thermal energy harvesting: It is based on the principle of harvesting energy from environments or objects at different temperatures through heat transfer, and this way it produces an electrical voltage between the hot and the cold junctions [57,58]. Although the use of thermoelectric generators sounds promising, the efficiency of thermoelectric generators is very

low, around 5.5% for a heat difference of 17°C, due to the Carnot cycle [57]. Energy density of thermal energy harvesting is around 100 μW/cm^2 at a 5°C temperature difference and 3.5 mW/cm^2 at a 30°C temperature difference [57].

- Vibration energy harvesting: It is based on the principle of producing energy from mechanical vibrations using a conversion process falling into one of the following methods: piezoelectric method, electrostatic method, and inductive spring-mass system [23,57]. Depending on the energy harvesting requirements and size limitations of proposed devices, one of these methods can be chosen. The energy density of vibration energy harvesting using piezoelectric method is 100–330 μW/cm^3 [59].
- Air flow energy harvesting: It harvests energy from air flow using a number of approaches with different principles such as microscale wind turbines, flapping wings, and oscillating wings. The efficiency of all the air flow energy harvesting approaches directly depends on the collector area specified by a combination of a set of parameters such as air speed, air density, conversion efficiency, and power output. Energy density of air flow energy harvesting is around 3.5 mW/cm^2 when air flow speed is 8.4 m/s [85].
- Electromagnetic wave energy harvesting: It harvests energy from electromagnetic waves. The efficiency of electromagnetic wave energy harvesting depends on the magnitude of electric field created by the output power of one or more transmitters [23]. Although power grid environments are energy rich and therefore this approach seems promising, wireless MEMS devices must be located away from such powerful transmitters to operate properly. Energy density of electromagnetic wave energy harvesting is around 15 mW when an AC-powered RF source transmits at 906 MHz with 3 W transmission power at a distance of 30 cm [61].
- Magnetic field energy harvesting: In power distribution environments, it harvests energy from magnetic fields existing near transmission and distribution lines [58]. Most of the devices that harvest energy based on this principle rely on the transformer action; hence, they require a clamp around the conductor.

Since the energy requirements of wireless MEMS devices are very low, one of the existing or emerging microscale energy harvesting solutions can be chosen depending on the device specifications and deployment environment. However, since most microscale energy generation/harvesting solutions are not always available, they must be complemented with suitable storage solutions. An alternative energy harvesting solution is modulated backscattering, which allows the wireless devices to send their data by just switching the impedance of their antennas and reflecting the incident signals coming from AC- or DC-powered RF sources [7,62]. However, harsh and complex power distribution environments make the practical and reliable implementation of this approach questionable.

Since the integration of harvesting mechanisms into MEMS devices is hard due to size limitations, microscale combustors and micro fuel cells are sometimes preferred since they are highly successful in size restricted devices such as MEMS devices. Compared to conventional batteries, fuel cells can produce much more electrical energy per unit weight, even when their low conversion efficiency is taken into account [63]. For instance, hydrocarbon fuels provide energy density around 50 MJ/kg whereas most lithium ion batteries provide energy density up to 0.7 MJ/kg [15,16].

Considering the efficiency of available energy harvesting solutions and the lifetime of energy storage solutions, a set of node-level optimization approaches that are based on adjusting a group of parameters related to sensor nodes should be considered [7]. For instance, duty cycle, rate of sampling, transmission power, data processing tasks, and reliability of sensing are important parameters in the lifetime of sensor nodes [7,20,64,65]. In this respect, solutions that enable the prediction of harvestable energy can help to tune several parameters to improve node lifetime [66]. Some approaches such as the tuning of sensing-related parameters, hierarchical sensing, the sampling of interesting intervals of time and regions of space, and the prediction of measurements can also help in improving node lifetime [7,67]. Finally, an important tradeoff lies between the tuning of system parameters and node-level design adaptations.

Network-level optimizations can greatly help in extending the lifetime of the wireless sensor networks consisting of wireless MEMS nodes. For instance, routing protocols/techniques with metrics to account for the residual energy levels of nodes, cluster-based routing mechanisms, data gathering methods based on energy-efficient approaches, and media access control protocols using more efficient approaches to utilize the harvested energy in order to maximize network throughput, minimize delays, and improve reliability [68] are examples of such optimizations [66].

11.4 Research challenges

SG transformations force the electric utilities to consider the need for renewal that involves the increased incorporation of SG technologies and at the same time the replacement of old equipment. This is because the SGs must continue to evolve in response to changes such as increased reliance on demand response programs, the development of distributed renewable energy resources, the refurbishment of old nuclear generators, the shutdown of coal-fired generation, and integration of various energy storage technologies. Therefore, the electricity system must be able to meet all these challenges without scarifying reliability, efficiency, and flexibility through the implementation of novel SG technologies such as wireless MEMS devices.

In the absence of interoperability and cyber security standards, some concerns may arise in AMI deployments due to the use of closed and proprietary systems that may be incompatible with common data communication protocols and standards [60,69]. In addition, electric utilities must be able to seamlessly integrate the various streams of operational SG data into intelligent software-based tools used for planning and other asset decisions. In this respect, wireless MEMS devices must be designed taking into consideration interoperability issues and existing cybersecurity standards.

Since an SG relies on a set of solutions provided by different applications and requires a sophisticated communication infrastructure that provides two-way communications links, real time information flows, DR programs, load management technologies, and active consumer participation, the management of such a complex system is a big challenge [25,70]. Moreover, the cost of wireless MEMS devices is less than the alternative devices, and hence the implementation and use of wireless MEMS devices for various tasks in SG environments will make the SG more distributed.

SG communication infrastructure must be prepared for critical situations such as earthquakes, hurricanes, ice storms, and terrorist attacks. The resilience and survivability of the communication is very important for the quick recovery of the communications because almost all SG applications rely on the real-time delivery of data gathered from millions of devices and sensors [71]. Therefore, contingency steps such as redundant communications links, power backup facilities, and emergency situation planning must be in place to ensure reliable communication during critical situations [72,73]. In addition, the survivability of the communication networks in possible critical situation scenarios must be tested using realistic simulation platforms and hardware-in-the-loop technologies.

Due to the unique characteristics of wireless channels in power distribution environments, the following problems are experienced in SG communication networks [74], especially in outdoor substations, indoor power control rooms, and underground network transformer vaults. Therefore, communication technologies proposed for wireless MEMS devices must evolve into more sophisticated ones considering these challenges:

- High bit error rates;
- Packet drops;
- Long and variable propagation delays;
- Fading;
- Multi-path effect;
- Retransmissions.

11.5 Open research issues

It is well-known that since it directly affects their operational time, energy is the most important requirement of all kinds of wireless devices, including wireless MEMS devices, though the energy need of the wireless MEMS devices is much less than the others. In this regard, although energy storage technologies have progressed in recent years, the operational lifetime of wireless MEMS devices is still determined by their batteries. After a while, even if the device components are still functional, the device becomes unusable if its battery is depleted.

The power density of lithium ion batteries is much less than combustion devices. Therefore, microscale combustion devices are good options for wireless MEMS devices in power grid environments and wireless sensor networks as well [75]. On the other hand, integrating such microscale combustion devices using MEMS technology is very hard due to the distinct limitations of MEMS devices such as size, assembly, sealing, and fabrication. Therefore, one of the important research topics related to powering MEMS devices is the practical and low-cost development and integration of microscale combustion devices.

The development of energy-efficient cross-layer communication protocols specifically designed for SG communication is one of the most important research issues. It is expected that such protocols can handle link quality variations efficiently, ensure reliable packet delivery, support QoS provisioning, and provide coordinated network management capabilities for different SG applications.

SG elements must be designed and deployed with security standards in mind. A holistic approach that includes public key infrastructure technical elements and trusted computing elements must be followed [76]. However, to achieve this, many steps need to be taken, including the need for a comprehensive and coherent set of requirements and standards for SG security [77].

Ferroelectric MEMS technology can be used for several applications in power distribution environments such as gas flow meters, diagnostic sensors, nanoporous solar cells, room light controllers, micro power generators, energy harvester modules, light modulators, proximity sensors, micro pumps, and solid oxide fuel cells [78,79]. However, although MEMS technology offers many benefits to electric utilities, it has not been proven well in the context of the regulations, architecture, configurations, and desired specifications of the utilities. Given the critical role of the SG, MEMS devices must be tested and validated thoroughly in near real-world scenarios before deployment [80].

One of the most important key trends that drive information technologies is cloud computing. It allows the integration of data and computing capabilities from multiple and typically highly diverse sources to deliver powerful software applications over the Internet. It provides the flexibility, scalability, and security needed for emerging applications. Cloud computing can be easily implemented in SGs and augment the existing and emerging utility capabilities [81,82].

Machine learning techniques allow information systems to evolve behaviors based on empirical data such as the phasor measurement unit (PMU) and sensor data [83]. For instance, they can be used to analyze different types of renewable energy sources to choose the best one that maximizes a desired goal. Considering the fact that SGs include millions of smart meters, sensors, and PMUs, machine learning techniques can play important roles in the analysis and processing of data and grid states [83,84].

11.6 Conclusion

In this chapter, commonly used SG applications, along with their typical requirements, and a detailed review about the use of wireless MEMS devices for SG applications and in power system environments have been presented. In addition, a review of communication standards implemented in power system environments and power sources for wireless MEMS devices has been given. Finally, open research issues have been outlined and research challenges have been presented.

Although the use of wireless sensor nodes in power distribution environments has been investigated extensively by both researchers and academicians, and those devices are used by many utilities around the world, wireless sensor nodes produced using MEMS technology have not replaced traditional wireless sensor nodes. In this respect, there are both research challenges due to the limitations of MEMS technology and several open research issues waiting to be handled.

Acknowledgments

The work of V. C. Gungor was supported in part by the Turkish National Academy of Sciences Distinguished Young Scientist Award Program (TUBA-GEBIP) under grant no. V.G./TBA-GEBP/2013-14.

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