Abstract—The deployment of advanced metering infrastructure (AMI) in electric power systems aims to help utilities improve the customer service and achieve utility operation cost savings by enabling and enhancing a set of utility applications. This paper presents an overview of current AMI technology and analyzes its potential problems. One problem is that the metering system lacks functions including local data management and peer-to-peer interaction and has no common platforms and open designs. In addition, the hierarchical communication structure and the centralized data management model may lead to a delay in communication between meters and data management systems and create a heavy burden for both communication and data management systems. Regarding these problems, this paper proposes different levels of improvements that will advance AMI technology. The goal of these improvements is to (1) achieve distributed intelligence at premise sites to reduce the burden in both communication and data management systems and (2) speed up system information access via the internet/intranet mechanism.

Index Terms—Advanced metering infrastructure, Electricity meter, Data management, power system, Wired/wireless communication, Smart Grid.

I. INTRODUCTION

The electric power industry refers to the system of measuring, collecting, analyzing, and controlling energy usage using advanced electricity meters, various communication media, and data management systems as the advanced metering infrastructure (AMI). An AMI system is comprised of comprehensive, integrated devices, networks, computer systems, protocols, and organizational processes [1]. AMI technology allows the two-way transmission of customer energy usage data and utility control signals between customers and utility control centers.

The predecessor of AMI is the automatic meter reading (AMR) technology. The development of AMR technology began in the 1960s [2] and has received considerable attention since the late 1990s with significant improvement in digital solid-state, computer, and communication techniques that are essential to AMR technology [3-5]. AMR provides utilities with the ability to remotely and automatically collect customer energy consumption data from electricity meters at customer sites. The primary use of the data collected through AMR systems includes flexible customer billing, prepayment options [6], outage management [2, 7-10], tamper/theft detection [11], and other functions. These utility applications based on AMR data can improve the operational efficiency and customer satisfaction [12, 13].

Compared to AMR, AMI technology provides a more advanced infrastructure and functionalities, including full two-way communication, remote connect/disconnect operations, demand response, and so on. These advanced features of AMI technology not only enable utilities to meet their business needs for meter data collection but also empower utility customers actively and frequently participate in demand response and energy conservation [14-17]. For example, the demand response function can assist utilities working with customers to shift load off peak load hours for economic energy usage and/or system reliability preserve. Therefore, AMI technology can effectively address the challenges that power industry faces, such as the restriction in energy supply and delivery systems.

AMI technology is crucial to the future smart grid [18, 19], which refers to future power systems that has grid reliability and efficiency because they can automatically anticipate and respond to power system disturbances [20, 21]. The functions that AMI technology can perform such as the delivery of valuable grid information for better energy-management decisions, timely access to detailed usage data, and the monitoring and control of energy usage at the meter level, can significantly improve the predictive and self-healing abilities essential to the tomorrow’s smart grid.

II. AMI TECHNOLOGY OVERVIEW

An AMI system generally consists of three basic components: (1) a metering system, (2) a communication system, and (3) a data management system. The metering system, which serves as the backbone of an AMI system, is to measure consumers’ energy usage profiles and communicate the data to the communication network. The communication system is responsible for transmitting information from meters to the data management system. The data management system processes the collected meter data and provides information to customers and utilities. This section summarizes the techniques used to implement the three parts of an AMI system and the functionalities that each part can achieve.

A. AMI Metering System

The AMI metering system consists of all the electricity meters installed at customer sites that perform both measuring
and communication functions. The current electricity meters adopted in AMI systems fall into two basic classes: (1) traditional electromechanical meters with retrofitted communication modules and (2) advanced digital solid-state electricity meters.

The electromechanical meter operates by counting the revolutions of an aluminum disc, designed to rotate at a speed proportional to the power. The number of revolutions, which is proportional to energy usage, determines the amount of energy consumption during a certain period [22]. Traditional electromechanical meters generally have no communication capability and must be read manually by either representatives of power companies or customers. Some meter companies have developed communication modules that can be retrofitted in electromechanical meters so that customers do not need to purchase new meters while obtaining the benefits of automated metering.

While traditional electromechanical meters in the field have provided reliable and dependable services, the industry seeks to reduce operational costs by expanding metering functionality and at the same time improve operational performance. To meet this need, the solid-state electricity meter is considered an effective solution. Solid-state electricity meters refer to the electronic meters based on digital signal processing technologies. Solid-state meters generally use the microprocessor and related techniques to convert analog signals to digital signals, process digital signals, display information, and direct communicate with other devices [23].

Wireless communication technologies including low-power radio, GSM (global system for mobile communications), GPRS (general packet radio services), and so on are equipped with meters in AMI systems to transmit measurements to and receive instructions from the communication system [1]. In addition to kWh consumption generally measured by electromechanical meters, the solid-state meter is also able to provide demand interval information, time-of-use (TOU), load profile recording, voltage monitoring, reverse flow and tamper detection, power outage notification, a service control switch, and other capabilities.

The advanced measuring and communication functionalities of solid-state meters and electromechanical meters retrofitted with communication modules add accuracy and flexibility to the AMI metering system and provide powerful network management possibilities.

B. AMI Communication System

The AMI communication system works as a data or information transmitting system that transports customer measurements and utility control signals from the AMI metering system to the data management system and vice versa. While a variety of communication techniques have been deployed in AMI systems, some AMI vendors [24-28] have also developed proprietary equipment that facilitates an effective communication function of their own AMI products.

Communication technologies used in current AMI systems fall into two fundamental categories: (1) wired communication and (2) wireless communication. Wired communication includes communication via telephone systems, the Ethernet, power line carriers, broadband over power lines, and so on. Wireless communication includes communication via mobile systems, cellular networks, wireless mesh networks, and others. The communication system can work in either a one- or two-way mode. Compared to one-way communication, the two-way communication system requires more expensive devices that can enable bidirectional communication. The following sections will summarize the features of wired and wireless communication technologies.

B.1 Wired Communication

Communication technology via the telephone or the Ethernet requires that a telephone cable or Ethernet wiring be available for all meter placements. The costs of cables and telephone modems limit the use of this technology in many applications. Power Line Carrier (PLC)/Broadband over Power Line (BPL) technologies offer AMI a means of transmitting data over existing power lines as an alternative to constructing a dedicated communication infrastructure. Although such solutions require no infrastructure, data transmission over power line networks is known to have such problems as open circuits, high distortion, and others.

B.2 Wireless Communication

Wireless technologies enable communication without wiring and compared with wired communication, have the following advantages: (1) offering less intrusive and more convenient installation and (2) involving no wiring installation and material costs. An overview of several wireless communication techniques currently deployed in AMI systems is provided as follows:

Cellular Network With wireless communication, the existing wireless cellular network can be the communication infrastructure and provide a two-way communication solution. However, this technology suffers from limited coverage in rural areas.

Wireless Mesh Network A wireless mesh network is a two-way communication technology that meters can communicate with each other and with gateways. All meters and gateways then form a self-organizing, self-healing network and maintain connectivity in a decentralized manner. Control of the communication network is distributed among the meters, which enable redundant communication paths throughout the network. If one path to a destination is not effective, a more effective path is automatically taken. This technology can provide high fault tolerance, and it has self-configuration, self-organization, and self-healing capabilities.

C. AMI Data Management System

The AMI meter data management (MDM) system provides a set of advanced software tools that manage large volumes of
Ⅲ. APPLICATIONS OF AMI TECHNOLOGY

A well-developed AMI system can facilitate more accurate and efficient performance of a variety of utility applications, which will ultimately improve customer service and achieve operational cost savings. These applications include automated meter reading, outage management, demand response, tamper/theft detection, energy usage prepayment option, distribution system state estimation, and so on. This section briefly illustrates improvements resulting from the use of AMI technology in these applications.

**Automated Meter Reading**

The manual reading of meter data is costly and time-consuming. AMI can eliminate expenses related to manual meter reading by substituting it with automated meter reading techniques. Automating the meter reading process improves the accuracy of meter readings and minimizes the possibility of missing a reading, eliminates the need for an estimated customer bill, and reduces customer complaints and call center traffic. In addition, certain that their meter readings are accurate, customers are less likely to dispute a bill and more likely to pay on time, which reduces the need to re-read meters at extra cost.

**Outage Management**

Most electric utilities currently rely on a trouble call system to inform the occurrence of power outages, i.e., when a permanent fault occurs and customers experience a power outage, customers usually call the distribution system control center and report the power outage. The distribution control center then sends out crew people to investigate the fault location and restore electricity services. The absence of customers may delay the power outage report and service restoration. The automated outage notification function provided by AMI systems can assist the outage management system with providing a timely and accurately determination of fault locations, save the company crew time in the detection of the fault location, and speed up the service restoration procedure. The restoration notification function of AMI can also help to monitor restoration to ensure that power is fully restored.

**Demand Response**

Demand response (DR) refers to changes in electricity use by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. DR involves the broadcast of pricing signals to consumers so that they have the option to cut back on their power usage. The AMI system can achieve this function by (1) communicating DR signals to customers in wide areas, i.e., provide time-based rates to customers that reflect the variation in utility supply costs with time and (2) controlling the power usage at the meter level or through the meter to an even lower appliance level according to a predefined mechanism.

**Tamper/Theft Detection**

The illegal use of electricity seriously threatens utilities in terms of both economic and safety concerns. Much of the lost revenue can be attributed to meter tampering and current diversion. A tampered meter can cause burns, severe injuries, or even death to thieves, bystanders, and utility personnel. While police departments and special security forces spend time and resources attempting to solve this problem, AMI technology can provide automatic solutions such as comparing the load profile data with historical records or reporting a tamper switch being triggered at a customer site.

**Prepayment Option**

Electric utilities generally bill consumers for the amount of energy used in the previous month or quarter. However, an alternative payment option that some customers find convenient is the prepayment option. The prepayment option requires the customer to send a payment in advance, or before the electricity can be used, and once the prepayment is used up, the supply of electricity is cut off. Most electromechanical prepayment meters accept only cash and require regular visits to remove cash from the meter sites. The solid-state meters in AMI systems together with smart card technology enable customers to use a smart card instead of cash to recharge the prepayment meters, which cancels regular visits as required traditionally.

**Distribution System State Estimation**

State estimation is a computational procedure that uses a redundant set of measurements to compute the best estimate of the system network topology and the operating state. Accurate and reliable knowledge of the system topology and the operating state are essential for system operators, who must effectively control and operate power systems. Estimating the distribution system state has been challenging because of the features of distribution systems, such as the three-phase unbalanced system and limited real-time measurements supplied by distribution SCADA systems. Since more complete and real-time system data at customer sites provided by the AMI system, such as customer energy usage, meter-level outage and restoration notification, and voltage information at customer delivery points, can supply more accurate and redundant measurements to distribution system state estimation, the state estimation output is more precise and trustworthy.

Some other applications based on AMI technology include net metering, remote meter reading on demand, flexible billing options, and others. Many more advanced applications such as asset management, feeder automation, and so on will also benefit from AMI technology.
IV. Evaluation of AMI Technology

Based on the information of current AMI technology illustrated in the previous sections, an evaluation will be conducted on the techniques used in the three components of the AMI system in this section: (1) the metering system, (2) the communication system, and (3) the data management system.

A. AMI Meters

Current AMI systems either use standard electromechanical meters retrofitted with communication modules or adopt more advanced solid-state meters. Most of these meters have a two-way radio wireless communication function, and they can send meter data to and receive instructions/control signals from communication systems. The major disadvantage of electromechanical meters is their limited and nonexpendable measuring functionalities. Compared with electromechanical meters, solid-state meters provide more flexible metering functions, and they can measure and process different types of data. However, solid-state meters exhibit following several drawbacks: (1) Meters have no local data management functionality. All the meter data has to be sent to the central data management system. This centralized data processing model significantly increases the burden for both the communication network and the data management system; (2) Meters have no peer-to-peer functionality interaction. Instead, each meter works individually and has no further interaction with other meters besides using neighbor meters as communication paths in the mesh network; (3) Meters are generally developed based on various microprocessors that have no common platforms and open designs. Most meters, therefore, do not allow simple, automated expansion and upgrading.

B. AMI Communication Network

Most of the current existing AMI communication networks can fulfill two-way communication between meters at customer sites and data management systems at utility control centers. However, these AMI communication networks generally require the installation of some types of gateways, or data collectors. The functions of such gateways/collectors include (1) collecting and temporarily storing meter data and sending the data to data management systems and (2) conveying requests or control signals from the utility control center to the meters. Each gateway/collector can handle a certain amount of meters, and one communication network may include multiple gateways/collectors. Such a hierarchical or tree-like communication structure exhibits the following problems: (1) In the communication procedure, the meter data are sent to the gateways/collectors first before they can reach the data management systems, and vice versa, instruction/control signals from utility control centers must go through gateways/collectors to be sent to the meters. The meter data and control signals that are desired to be communicated in real time can be delayed by this communication procedure; (2) Each gateway/collector can handle only a certain number of meters. Handling more will pose a risk to the performance of the communication network. When new areas of service are expanded and new meters installed, additional gateway/collector installations must then be installed accordingly; (3) The hierarchical structure leads to low error tolerance in the communication network. If some gateways/collectors do not work properly, they will not be able to collect meter data and convey control signals, which will interrupt customer service based on meter data, and it could also result in blackouts if load reduction signals are blocked or delayed.

C. AMI Data Management System

Current AMI data management systems collect all meter data from the communication network, store the data in the central database, and process the data to extract valuable information for various utility applications. However, this data management system working mode may lead to a situation in which a large quantity of meter data and customer on-line requests may become too heavy a burden to data management servers when a large number of meters are deployed in the AMI system.

The root cause of these problems in current AMI systems is that the current AMI is implemented based on existing metering techniques, including electromechanical and solid-state meters, which were not specifically targeted to AMI technology. Although electromechanical and solid-state meters contain basic functions required by AMI systems, and they can fulfill some AMI functions once they have been supplied with communication modules and gateways/collectors, more advanced features and some key application performance expected from the AMI technology are limited by such meters and their augmented communication techniques.

V. Enhancement of AMI Technology

The evaluation of current AMI technology identifies drawbacks existing in the present AMI metering and communication systems and their impact on the data management system. This section will propose some potential enhancements in AMI metering and communication techniques that resolve these problems and advance the state of the art in these areas. The goals of improving AMI metering and communication techniques include (1) implementing a local data management system for distributed monitoring and control, (2) reducing the heavy burden of communication systems and centralized data management systems, and (3) increasing the upgradeability and expandability of metering and communication systems. Specifically, AMI technology enhancements can be achieved at different levels:

Level 1: Development the local data management functions based on solid-state meters

Level 1 enhancement in AMI technology can be achieved based on the current AMI metering and communication infrastructure. In particular, currently used solid-state meter functionalities can be extended to (1) realize master-to-slave/peer-to-peer interaction among neighboring meters and (2) implement local meter data management and control. This level of AMI technology enhancement aims to achieve distributed intelligence applications based on solid-state meter
techniques that can reduce the burden on communication and centralized data management systems and increase the distributed intelligence level of the AMI system. In addition, such improvement is a low-cost solution as it focuses on meter functionality extension without changing the current AMI hardware infrastructure. This solution, however, cannot solve such problems caused by (1) meters that have no common platforms and open designs, which prevents simple, automated expansion and upgrading and (2) the hierarchical communication network.

**Level 2: Substitute the hierarchical communication network with a meshed, IP-based communication network**

The main purpose of Level 2 enhancement in AMI technology is to change the communication infrastructure from a hierarchical structure to a meshed, IP-based communication network, and at the same time, continually adopt solid-state meters in the metering system. This change in the communication structure is based on the development and adoption of a new type meter. This new type meter should be an IP-based computing platform and can be used as a meter and a gateway. We refer such meter as iMeter and it has following features: (1) Each iMeter is an IP-based device capable of gaining access to servers and other iMeters through a wired or wireless IP-based network in order to share meter data. Such an IP-based network communication mechanism provides more robust communication capabilities compared with the hierarchical communication structure currently used in AMI systems; (2) Each iMeter can work as a meter and a gateway at the same time. It can measure multiple types of data at customer sites and communicate with a certain number of electromechanical and solid-state electricity meters in the neighborhood (master/slave model) through available communication techniques, such as wireless radio frequency communication. The iMeter works as a master device to poll neighbor meter data, send control signals to neighbor meters, perform local meter data management and control in the neighborhood, and other tasks; (3) The functionalities of iMeters can be easily upgraded by downloading and installing the updated package through the internet/intranet network, and the security communication techniques developed in the area of IP-based internet/intranet networks are applicable to AMI communication systems.

In summary, the iMeter works as a computing platform that integrates the functions of the meter, the gateway, and the local data management functions together. In addition, the iMeter enables the application of a meshed, IP-based internet/intranet communication network in AMI communication systems that can achieve a more robust and fast communication functionality compared with the hierarchical communication structure. Furthermore, as an integrated part of the entire AMI system, the iMeter enables distributed intelligent applications in distribution systems, such as distributed calculation, analysis, and control functions based on local/neighbor meter data and network information. Distributed intelligence achieved via the iMeter can reduce the burden in both network communication and centralized data management servers by digesting meter data locally and sending only necessary information to the utility control center. Figure 1 shows an example AMI system that adopts iMeters and has the IP-based internet/intranet communication structure.

**Level 3: Further application of iMeter to replace electromechanical and solid-state meters**

Level 3 enhancements in AMI technology focus on improving both metering and communication systems, i.e., if possible, the iMeters can be used to replace all electromechanical and solid-state meters. In this way, each meter itself is an IP-based device, and all meters and servers constitute an IP-based internet/intranet communication network in which each meter can share information with other meters in the network and servers in the control centers. The IP-based network enables the most direct link between customers and utility control centers. In the network, each meter can work as a master device to poll neighboring meter information and conduct local data management functions. Meters in the same neighborhood can work in a peer-to-peer mode to verify local control decisions with each other. Figure 2 shows an example AMI system that adopts iMeter as much as possible and uses the IP-based internet/intranet communication network. Note that in areas that no IP-based network is easily accessed, the traditional meters (electromechanical and solid-state meters) as well as available communication techniques (such as radio frequency wireless communication) can still be adopted.

Among the three levels of enhancements in AMI technology, the Level 1 solution costs the least, but it can add only local management functions, which have to be developed based on various solid-state meter platforms and a communication structure that is still in the hierarchical form. The Level 2 solution is the most cost-effective technique. It continues to use electromechanical and solid-state meters and the iMeter is added to each neighborhood to communicate with all meters in the same area and other iMeters. This working mode can perform local meter data management and provide a meshed, IP-based communication network that improves communication performance and reduces the burden on both communication and central data management systems. The Level 3 solution is the most advanced, as each meter is an IP-based device. However, this solution incurs the greatest...
cost, as every customer site need to adopt the iMeter if possible.

Figure 2: Level 3 enhancement in AMI technology

VI. CONCLUSIONS

AMI systems are the new generation of metering systems that facilitate a wide range of technologies for both the customer and the electric utility. AMI involves a high level of automation and two-way communication that enable advanced applications. Utilities use current AMI technology mainly for automated meter reading, enhanced outage management, peak load management, and other tasks to improve customer service and save operational costs. This paper proposes different levels of solutions to improve current AMI technology that can provide more distributed intelligence, expandability, and upgradeability in metering and communication systems. These solutions can be implemented based on existing metering techniques, iMeters, and a standard internet/intranet communication mechanism. The improvements brought by these solutions in AMI technology can reduce the burden of both communication and central data management systems.

VII. REFERENCE