Recent Advances in Smart Grid Communication and Networking

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Abstract --**The smart grid emerges as the next generation electrical power grid with the capability of producing, transmitting, distributing, and consuming power in the most efficient and intelligent way. For achieving a smart electricity grid infrastructure, it is very critical for electric utilities to define the communication requirements and find the best communication infrastructure to handle the data and deliver a reliable, secure, and cost effective service throughout the total system. The 5G cellular network with low latency, high throughput, and high reliability can bring new solutions to smart grids. This promises high efficiency in the power distribution networks which results in more availability of power at homes and industries at low cost and will allow distributed renewable energy generation from local solar power and power generated by wind-powered turbines. The home energy management is part of the smart grid on the consumption side to collect data from home appliances using smart meters. This data is used for optimizing the supply of electrical power and distribution. It also includes intelligent controls in home appliances, giving consumers more choice and control over how and when electricity is used, which can save money and help grid to operate its electricity network more efficiently and reliably for the benefit of all its customers. Smart grid plays an important role in reducing green house gas emissions and other pollutants, especially in how it can facilitate the connection of large amounts of renewable energy with current electricity distribution system. This paper attempts to discuss recent advances in smart grid communication and networks by investigating its network architecture and communication technologies including integration of renewable energy sources and vehicle-to-grid technology.**

Keywords: IoT, Grid, 5G, Renewable energy, Vehicle-to-grid technology

I. INTRODUCTION

SMART gird is a new paradigm to design and operate the electrical power system with the objective to improve efficiency, enhance service quality, and save cost in power generation, transmission, distribution, and consumption. Information and communication technologies (ICT) are adopted in the smart grid to achieve these objectives. The 5G cellular network and smart grids are both important for the future development of the ICT industry.

Today there is a much perceived wastage of electricity in the way that one uses appliances and devices (for example, leaving devices on standby, inefficient usage of washing machine and refrigerators, insufficient use of heating and cooling), there is a plenty of scope for automated energy consumption methods. To address smart grid communication based on the current power grid system, cellular mobile communication systems are incorporated over power-line systems.

Cell phones can be used as an instrument to display information and allow consumers to control appliances in their homes in addition to the deployment of smart meters. This could be as simple as SMS message in a cell phone, whereby consumer receives an SMS when the tariff passes above a certain level, enabling them to make an informed decision as to whether they wish to turn off their appliances. With this, the smart grid applications can be realized economically and conveniently. The smart grid is expected not to require human intervention in characterizing power requirements and energy distribution. However, there are many challenges in the design of smart grid communication networks whereby, the electrical appliance and smart meters are able to exchange information pertaining to varying power requirements [1].

The paper attempts to discuss recent trends in intelligent smart grid using communication and networking by investigating its network architectures, 5G cellular communication technologies, and required Quality of Service (QoS).

II. SMART GRID

Traditional power grid consists of power generation, transmission, distribution, and consumption. The power is generated by different types of power generators, *e.g.*, hydroelectric, atomic power, coal-fired, and renewable energy like wind-powered turbines and solar power plants. A power generator measures the cost, power demand, and power prices offered by other types of generators to competitively or cooperatively adapt the power generation strategy and to achieve the maximum profit while meeting constraints on demand, capacity, and reliability. The existing power grid was built for unidirectional energy flow from power station to end customers. The power is delivered from power plant to the end users through the transmission substation (TS) located near the power plant and a number of distributed substation (DS) located near consumers.

The TS delivers power from power plant over high voltage transmission (230KV) to DS. The DSs are placed in different regions and convert the electrical power to medium voltage level. The power distribution has to be optimized so that the loss and cost of transmission are minimized given constraints on the amount of transmitted power and transmission line capacity. The distribution can be adaptive towards power generation and consumption side. The DS then distributes power to the feeders. The feeders further convert the medium level voltage to a lower level. A city has many neighborhoods, each neighborhood has many buildings and each building may have number of apartments. The power is consumed in homes, industries and commercial offices.

The power demand of consumers has to be determined to allocate power supply and distribution optimally [2].To achieve such a goal, the smart meters are deployed to quickly and accurately collect the power consumption data. This data can be used to estimate the power demand. Smart meters with current and voltage sensors monitors using wireless communication technology in such a way so that the customers and utilities can closely monitor energy usage and reduce consumption when the availability of electricity is stretched to its limit and proactively make repairs before an outage takes place [3].

Smart grid helps consumers to understand economies of their consumption patterns that they can make intelligent decisions about their power consumption. There are two essential elements to any smart grid design: a smart meter that can measure electricity consumption by the hour at each point of delivery, and tools for the customer to control their consumption based on factors such as the current tariff being applied based on time of the day, the loading on the energy grid, and environmental concerns *i.e.* whether the energy is derived from a renewable source. The smart grid can also address the issue of renewable energy representing an intermittent source of power generation, with the addition of renewable wind and solar energy technologies, and small scale intelligent consumer appliances, heat pumps, and electric vehicles (EV) operating in reverse mode (Vehicle-to-grid mode). When customer deploys the renewable energy system, the smart grid allows customer to sell the excess electricity to the grid.

The smart grid technology is capable of bidirectional power flow including two-way communication to support to enhance and automate energy utilization to match the load curve more closely. The smart grid reduces network losses, increase the reliability of the grid, and allows large amount of variable renewable power to be connected to the grid. Moreover, they enable consumers to control appliances at their homes to save energy, facilitate domestic generation, reduce cost, and increase reliability and transparency. As such, the evolution towards smart grids in future can play an important role in implementing the single electricity market by increasing network security and reducing energy use while increasing consumer and social welfare. Smart grids open up possibilities for consumers to also become producers of electricity. They will have an essential role in de-carbonizing our economy by bringing more renewable and distributed resources to the electricity market. The benefit of the smart grid includes lower operating and maintenance costs, lower peak demand, increased reliability, power quality, and expansion of access to electricity.

USA declared its "Grid-2030" mission in April 2003 to provide every one, any time, any where affordable, clean, reliable and efficient electric power [4]. A report from technology research and analysis firm ranked India behind US and China out of Smart grid countries for smart grid investing through to year 2030 [5]. In India cellular mobile communication is very popular. It can be used in off-peak hours to avoid congestion. India has already implemented Wireless Wide Area Network 4G, 5G cellular networks that could be used in smart grids.

III. COMMUNICATION AND NETWORKING

A communication and networking system is the key component of the smart grid infrastructure. For achieving a smart electricity grid infrastructure, a huge amount of data from different applications will be generated for further analysis, control, and real time pricing methods. Hence it is very critical for electric utilities to define the communication requirements and find the best communication infrastructure to handle the output data and deliver a reliable, secure, and a cost effective service throughout the total system [6, 7]. Important design choices of smart grid include type of communication technologies, type of medium, to use single hop or multi-hop communication. Different communication technologies can be used for data transmission between smart meters and electric utility centers. Specific communication and networking requirements for major smart grid applications are data rate, latency, reliability, coverage, range, and security. The communication network for smart grid requires data transfer in a timely manner with adequate bandwidth and reliability via a two-way communication with low latency [8].

Wireless Communication Technology: The wireless communication technologies eliminate the need of cable installation. It is cost effective and flexible to deploy wireless technologies. The unified architecture can be obtained by combining multiple wireless communication technologies [9]. The satellite communication is very expensive with large latency and low data rates. The microwave communication works in LoS (Line of Sight) with licensed frequencies. Short range communication can be used for smart devices/appliances which requires low mobility, low data rates, and low power consumption. The Blue tooth IEEE802.15.1 can be used to connect smart electronic devices with Gateway. Another short range communication named ZigBee IEEE802.15.4 consumes low power with low data rates and covers short range of about

100m. The Wireless LAN (Local Area Network) IEEE802.11 is most popular, covers area around 300-500m with large data-rate, and works at unlicensed frequency bands with high power consumption. The medium range communication technologies like IEEE 802.11ah,af can cover the range around 1km or more. The cellular mobile communication is most widely deployed around the world with large coverage area and accommodates large numberof remote devices with a gateway known as base station (BS).

Cellular Mobile Network.: In cellular radio network, the geographical area is divided into number of small areas called cells. Each cell requires a base stations (BS). It reduces power usage and noise interference as well. It also allows the frequency reuse to increase the capacity. The Cellular network is divided into number of generations. The first generation (1G) provided analog voice calls only while second generation (2G) provided digital voice calls including SMS (Short Message Service). The 3G provided mobile web browsing while 4G- LTE (Long Term Evolution) provides video and higher data throughput. The 5G provides very high peak data rates (20Gbps) using enhanced Mobile broadband (eMBB), low latency (1ms) using ultra Reliable low latency communication (uRLLC), and very large connection density of IoT devices (1 million per square km) using massive Machine type communication (mMTC) [10]. It supports smart grid applications because of its distributed network and wide spread coverage nature.

To maximize benefits of wireless technologies, utility center needs to combine access to public 5G cellular network and deployment of non public network (NPN) private 5G networks that use mix of licensed, unlicensed, and shared frequency spectrum. The high cost limits adoption of 5G in IoT, but RedCap (Reduced Capability) of 5G will reduce cost of 5G devices for IoT use cases which needs more BW than 4G-Narrow band(NB)-IoT technology for critical data, voice, and video communication. A 5G technology enabled push to video device can capture detailed images of the equipments to be serviced and send the image to the expert for getting assistance which reduces fault duration and there will be no transportation requirement. The 5G enabled Augmented reality (AR)/VR(Virtual Reality) solutions will help maintenance personnel in better restoration. The 5G low latency can be used for mission critical use cases such as control. The 5G enables utilities to wirelessely connect to the entire distribution grid assets.

The 5G and Wi-Fi: Electrical utilities in smart grid adopt new technologies to generate and consume energy in efficient way. The utility center will utilize both 5G and Wi-Fi 6/6E, 7 for use cases that require faster speed, higher capacity, low latency, high reliability, and security [11]. To maximize benefits of wireless technologies, utility center needs to combine access to public 5G cellular network and deployment of non public network (NPN) private 5G networks that use mix of licensed, unlicensed, and shared frequency spectrum. The cost of 5G in indoor is higher than WiFi but5G is most cost effective than WiFi for outdoor wider area coverage. The high cost limits adoption of 5G in IoT, but RedCap (Reduced Capability) of 5G will reduce cost of 5G devices for IoT use cases which needs more BW than 4G-Narrow band (NB)-IoT technology for critical data and voice communication. However, the main advantage of Wi-Fi is low per-bit cost and ease-of-deployment.

IV. SMART METERING

The electrical utilities in smart grid adopt new technologies to generate and consume energy in efficient way. The smart meter is an electrical meter that records consumption of electrical energy in interval of an hour or less and communicate that information at least daily back to utility center for monitoring and billing purposes [12]. Smart meters enable two-way communication between meter and the central utility control system is called advanced metering infrastructure (AMI). The AMI is a system that helps electric utility center optimize the supply and demand of electricity through demand response programs and load management. By using pricing signals, utility center can encourage customers to shift their electricity consumption to off-peak times, when electricity is cheaper, through time- of-use pricing. Additionally critical peak pricing allows utilities not to be used during times of high electricity demand, such as hot summer afternoons, to prevent blackouts. The utility control center periodically enters into the contracts with power generators to purchase electricity through the distribution and transmission substations.

Using data on the estimated power demand from all appliances in a service area, the power generators determine the prices for the periodic contract. However, the data on power demand can be incomplete or delayed, leading to differences between the estimated and actual demand. If the estimated demand is higher than actual demand, there is an oversupply of electricity that is wasted. Conversely, if the actual demand is higher than the estimated demand, additional power must be purchased at a higher cost due to the instant need. The power generators typically tries to supply power from the cheapest source, such as hydroelectricity in normal circumstances while additional power required may be supplied by using thermal power station.

The AMI devices can provide utility center with detailed power quality measurements, such as voltage sags and harmonics distortion, which can help them plan network expansion and improve power quality. The networked sensors and smart appliances helps smart meters to collect outage, voltage, phase, frequency of data, detailed status, and diagnostic data. Basically two types of dataflow are needed in a smart grid system. The first data flow from sensors of electric appliances in house to smart meters, the second is between smart meters and the utility control centers. The data from sensors of electrical appliances located in house transmitted using ZigBee/NB-IoT to smart meter. The Smart meters from different houses collect data locally and transmit using Wi-Fi to a data collector/aggregator located at short distances from smart meters. The data from data collector are transmitted using cellular network to the utility control center located at large distance from data collector for processing and business applications [13]. The two-way communication helps to send signals or commands directly to the smart meters at customer premises.

V. HOME ENERGY MANAGEMENT

The Home Energy Management System (HEMS) is used in smart grids to monitor and control the power consumption of household appliances, such as air-conditioners, washing machines, refrigerators, etc. using smart meters. The data collected from these appliances is analyzed and optimized by a utility control center. At the consumer level, the load connected to and controlled by a smart meter is divided into different groups based on the type of load [14]. Small loads, like light bulbs and device chargers, do not significantly change the load profile and simply send notifications of connection and disconnection. Large loads, such as electric ovens and stoves, which may be used at any time, should not be controlled and the smart meter shouldbe informed of their expected power usage and duration. Other large loads, such as air-conditioners and washer/dryers, can be controlled and must receive acceptance from the smart meter before being switched on. The decision to turn on these appliances will depend on dynamic pricing and duration of availability.

A home-based charging station for a Plug-in Hybrid Electric Vehicle (PHEV) can also charge the electric vehicle overnight during off-peak hours, resulting in significantly lower charging costs compared to petrol charges per kilometer. Another type of load in EVs becoming more common in smart grids is Vehicle-to-Home (V2H). A V2H enables an EV to supply power to a home through a bidirectional charger, which coverts DC power from EV battery to AC power for the home during grid outages or peak demand periods, managed by energy management controller. This supports benefits such as emergency backup, cost savings during peak load, and grid stability contributions.

The communication network infrastructure can be partitioned into three segments, Home area network (HAN), Neighborhood area network (NAN), and Wide area network (WAN) or back-haul. The HAN can be established among home appliances and smart meter using Bluetooth or ZigBee as shown in Figure 1. The HAN gathers data from various smart appliances within the home and delivers control data to smart meter for better energy consumption management. It can make heaters or air conditioners off during peak load conditions.

Smart meters are equipped with power reading, and communication gateway interfaces that relay data from HAN to NAN. The HAN covers around 200m area. The smart meter at each residence aggregate HAN information and act as a bridge to the NAN. The NAN is established among smart meters of the houses in the area as shown in Figure The Smart meters from 2. Different houses collect data locally and transmit using Wi-Fi to a data collector/aggregator located at short distances from smart meters. The number of smart meters in each NAN cluster varies from a few hundred to a few thousand depending on the power grid topology and communication technology employed. The NAN transports a huge volume of different types of data and distribution control signals between utility control center and a large number of appliances installed at customer premises.

A NAN collects data packets from smart meters of the houses using short range communication like Wi-Fi. The transmission range is around 500m and can incorporate a multi-hop mesh network. The enhancement of NAN can be carried out using WLAN 802.11ah in band 902-928MHz or 802.11af in VHF/UHF TV band using cognitive radio to extend the range more than 1 km. The received packets are stored in the buffer. The status and demand data from smart meters of each house transferred to buffers are then forwarded to cellular network 4G-LTE or now 5G. The Wireless WAN aggregates data from multiple NANs and conveys it to the utility control center. It covers thousands of kms and could aggregate thousands of supporting NAN devices that requires 10-100Mbps of data transmission. The utility companies wireless WAN provides the 2-way network needed for substation communication, distribution, automation, power quality monitoring. This data is used to optimize the electric power generation and distribution.

Inter-working between cellular networks and WiFi has received a lot of attention because of the need for seamless mobility and QoS requirements. Smart grid, due to the extremely large scale nature of the network, the characteristics of the metering and control traffic carried in the network are clearly not known. In current standards, each smart meter sends a few kbytes of data every 15 minutes. When this is scaled upto a large number of meters. (*e.g.* 100,000 meters) many existing communication architectures may not have sufficient BW to handle it. To calculate the required throughput, it is necessary to consider the data generated by measuring line voltage and current, which can be around 2kbps per phase. In a three-phase power line, with three voltages and three currents, the data rate would be approximately 12kbps. However, other data, such as phase angle and sequence components, can further increase the data rate between 200-500kbps. These data rates, along with the overload of communication protocols like node addressing, error detection and correction, and routing, result in a significant higher bit rate. As a rough estimate, 2-5Mbps can be considered as low-to-mediumdata rate. Ensuring that this data can be reliably and efficiently delivered to the utility control center is a challenging task.

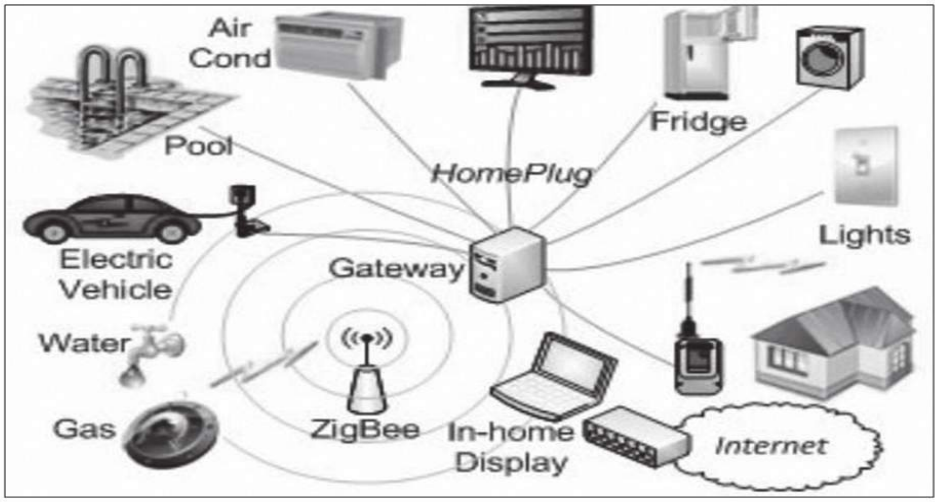

Figure1. Home Area Network (HAN) [15].

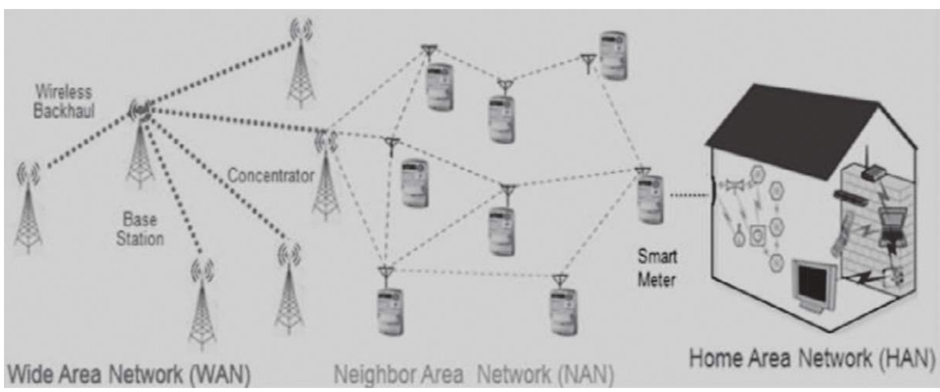

Figure 2. Smart Grid Architecture [15].

The utility control center periodically enters in to the contracts with power generators to purchase electricity through thedistributionandtransmission substations. Using data on the estimated power demand from all appliances inaservicearea,th epowergeneratorsdeterminethepricesfor the periodic contract. However, the data on power demand can be incomplete or delayed, leading to differences between the estimated and actual demand. If the estimated demand is higher than actual demand, there is anoversupply of electricity that is wasted. Conversely, if the actual demand is higher than the estimated demand, additional power must be purchased at a higher cost due to the instant need. The power generators typically tries to supply power from the cheapest source, such as hydroelectricity in normal circumstances while additional power required may be supplied by using thermal power station.

VI. VEHICLE-TO-GRID (V2G) TECHNOLOGY

Vehicle-to-grid technology is a way for electrical vehicles (EV) and smart grids to partner for efficient energy flow. The V2G technology enables the EVs to act as a portable energy storage station, physically bringing auxiliary power for the ride. The V2G allows EVs to communicate with the smart grid and to deliver and receive power on demand. To maximize energy usage it will require bidirectional energy flow to-and-from EVs including V2G charging technology. The V2G technology is essential to integrate renewable energy into the grid to maximize the usage. The wind and solar energy are intermittent energy sourcesandcanleadtopowerfluctuationwhereasV2Gcan store energy in the car battery when more power is needed. When there is lack of energy in the grid, the car can discharge the stored energy back to the grid. In V2G, aggregating pools of EVs can become virtual power plants (VPP) and export back to the grid when it is most needed, helping to balance supply and demand of electricity. A case study in Germany found that V2G could provide 200MW power to the city by2030, representing 20% of its peak-load during summer. The V2G will help in achieving net zero emissions aiming to reach this goal by 2050 worldwide. Educating the public about V2G will benefit individuals and promoting the use of EVs are also essential tasks. Increasing consumer awareness will increase adoption and improve chances for V2G technology to succeed.

VII. INTEGRATION OF RENEWABLE ENERGY

Renewable energy led by solar and wind are intermittent. The Sun is not always shining, and wind does not always blow. A solution is required to collect intermittent renewable energy, store it, and deploy it consistently for end-users. Integration of intermittent energy resources into grid presents new challenges. Renewable energy production is inherently variable depending on the weather conditions and time of the day. This variability leads to supply and demand mismatches, requiring energy storage or back-up power from non-renewable sources. Energy storage system particularly batteries, are essential for maintaining a consistent energy supply in grids that rely on renewable sources. The grid can store access energy from renewables during the day time and transmit it when needed, even at night or during blackouts.

VIII. AI IN SMART GRID

Artificial intelligence (AI) is an intelligent agent behind smart grids evaluating the environment and taking action to maximize a given goal. In order for smart grids to operate economically and reliably, demand forecasting is essential, because it is used to predict the amount of power that will be consumed by the load. This is dependent on weather conditions, type of day, random events, incidents, etc. The demand response can be provided by commercial, residential, and industrial loads. Artificial intelligence (AI) can be considered for demand forecasting. AI powered with smart grid management and smart metering allow customers to get hourly assessments of their power usage, helps them to see when and where they can use the most energy and optimize their typical daily routines to lower usage during peak hours. It helps consumers to manage energy production from renewable energy sources which can be sold back to the grid to reduce cost even further. AI plays a crucial role in unlocking the full potential of smart grids. By analyzing massive amount of data in real-time supplied by grid, AI algorithms enable smart grids to make decision about energy distribution, demand management, and system maintenance. AI continuously analyzes data from sensors and smart energy meters to monitor grid health and identify potential issues before they lead to problems. AI can detect voltage fluctuations, equipments malfunctions, or overloads, and automatically adjust the grid to balance supply and demand. AI can analyze trends in renewable energy production, adjusting it dynamically throughout the year. By utilizing excess energy storage capacity, these technologies can optimize the integration of renewable energy into the grid, ensuring a more stable and reliable energy supply. AI can further improve smart grid performance through automation and predictive demand modeling. The grid offers massive data to AI. The AI algorithms can analyze EVs battery health, grid conditions, electricity pricing, and EV usage patterns. This continuous optimization further balances the grid, lowers the electricity cost, and prolongs battery life, which is the highest component of EV cost.

IX. CONCLUSION

In this paper infrastructure of smart grid including integration of renewable energy and the 5G communication technology have been discussed including V2G, that can be utilized in a smart grid. Smart grids are transforming the way electricity is generated, distributed and consumed. The smart grids powered by AI represent the future of efficient energy distribution by optimizing energy flow, integrating renewable sources, improving grid resilience, and empowering consumers. The future of energy is not just smart, but it is intelligent, adaptive, and ready to power a greener tomorrow. The smart grids are a key focus for the communication and networking research due to the unique challenges and opportunities such as interoperability, scalability and security.

The success of future smart grids will depend on communication infrastructure, devices, and enabling software and services. Existing communication technology can be adapted to support large and complex smart grids, making it a valuable area of research for communication and networking. It is expected that smart power grids will continue to evolve in this decade with the adoption of 5G communication technology, providing enhance innovation, business scalability, and sustainable green societies through its low latency, high BW, and high reliability.

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