A Survey on Communication Infrastructure for Micro-grids

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Abstract – A micro-grid is a small scale power supply network that is designed to provide electricity to a small community with its own renewable energy sources. Due to distributed generation variability, security and load sharing issues, an efficient communication infrastructure is necessary between its agents (load, generation and storage units). Numerous research efforts are being developed to come up with such communication techniques that can overcome the barriers to implement the concept of micro-grids. This paper covers the features, characteristics and challenges of micro-grids and their associated communication techniques.

I. Introduction

Electric grids provide power (electricity) to consumers by generating it from various generation units/means. According to [1], the main grid is constituted by two primary delivery network systems: 1) the transmission system, which delivers power from power plants to distribution substations. 2) The distribution system, which delivers power from distribution substations to consumers. With this distribution network, which can be of thousands of miles, a substantial amount of energy is wasted in form of heat during delivering electricity to distribution substations, which eventually lowers the power quality and contributes toward global warming. The concept of Smart Grid was introduced by adding more intelligent and effective functionalities on top of electrical grid to balance the power generation and consumption, to reduce wasted power and to provide good quality to consumers.

The recent deployment in technology and the growing concerns of global warming motivated engineers to search for cleaner and more efficient systems to generate electricity. *"A Smart Grid is a cluster of interconnected distributed generators, loads and intermediate energy storage units (agents) that co-operate with each to be collectively treated by grid as a controllable load or generator"* [2]. Smart grid comprises the advanced sensing technologies, control algorithms, communication infrastructures and actuator for rapid diagnosis and to prevent and restore power outrages [18]. Our current power distribution infrastructure has one way communication. The initial conception of Smart Grid design was to have bi-directional communication infrastructure to support intelligent mechanisms such as real-time monitoring, protective relaying and to satisfy consumers' demand of power. As the Smart Grid concept moves toward its real implementation, there are some factors related to scalability, reliability and cyber security that are becoming major issues in materializing it. So, the need aroused for more flexible and efficient smaller smart grids that have local generation and storage facilities near the consumption premises. The term given to it is Micro-grid (MG).

A Micro-grid is a modern small scale electrical power grid infrastructure for better efficiency, reliability and integration of renewable energy sources. It can be characterized by two-way flow of power for the electrical network and information for the communication network [21]. This two-way power communication is beneficial for monitoring the condition of network and predicting failures, therefore reducing maintenance costs. MG can be seen as the division of a large-scale power grid into small community power grids. Each of these small community grids contains local traditional power generation and renewable energy sources; i.e. dividing the large smart grid area into smaller segments. Each of the segments is an autonomous, stand-alone grid [6]. MG increases the connectivity, automation and coordination between suppliers, consumers and networks that perform either long distance transmission or local distribution tasks [3]. The importance of MG as electrical generation systems has increased during last few years.

The introduction of MGs to a certain community is very beneficial in the case of university campuses, commercial facilities and residential communities because they can significantly reduce energy cost and carbon emissions by managing distributed generation systems to supply load and optimize energy use. In MGs, the main technologies advances are based upon two aspects: power electronics and wireless communication, as mentioned in [16].

This paper is structured as follows: Section II introduces operating modes in which MG can function. Section III focuses on characteristics and features of smart micro grids that influence the concept and their implementation. The importance of communications in MG is discussed in Section IV. Different building blocks that are required to implement MGs effectively are discussed in Section V. Various wireless technologies are presented in Section VI. Issues regarding communication infrastructure in micro grid is described in Section VII, and Section VIII summarizes the focal points and conclusions.

II. Micro-grid Modes of Operation

A MG operates in two modes: 1) grid connected mode and 2) islanded mode. Since the MG is connected to the main grid at only one point—the Point of Common Coupling (PCC), if some distortion happens, then the MG is disconnected through this “switch”.

In grid connected mode, the MG is connected to the main grid and provides electricity to its consumers from the latter, along with generating its own electricity from distributed energy sources and saving excess energy in storage units for future use. It can also sell/add excess of power to the main grid.

In islanded mode [14], the MG is disconnected from main grid and provides electricity from its own sources. If we want to keep operating the micro-grid, we need to transfer it to islanded mode of operation keeping the DGs spinning. This is a challenging change because traditionally, for protection reasons and based on available standards, DG units in a distribution micro-grid should be shut down following a disturbance in upstream network [4].

III. Characteristics of a Micro-grid

Given that a MG constitutes a segment of the Smart Grid, it inherits some of its characteristics. That is, the grid will have every characteristic that is required for smooth and reliable flow of power. Some principal characteristics of MGs according to the U.S. Department of Energy Modern Grid Initiative [19] are:

- MGs must have the capability to rapidly detect, analyze and respond to the fault (i.e. self-healing)
- They must be consumer friendly and involve a consumer into the grid operation
- They should be highly reliable and deliver the best power quality that satisfies the consumer needs
- They should be resilient to cyber and physical attacks
- They can accommodate variety of distributed generation and storage options and have the tendency to adapt to new technologies
- They should work in such a way that minimizes the operations and maintenance expenses.

IV. Role of Communication in Micro-grid

The role of communication is one of the major factors that are transforming the traditional grid into a set of micro-grids. An important aspect of concern in MGs is that they have variability in their power generation. This influence the two primary issues for the power distribution operation, i.e. voltage control and power flow management [20]. As an example of generation variability/voltage control, power output can increase or decrease in solar photovoltaic farms in the order of milliseconds as the cloud coverage changes. Similarly, power output for a wind farm can be completely lost on the order of minutes [5]. Likewise, if a relatively large load connects or disconnects without informing the rest of low inertia network in load sharing, similar instabilities can occur, e.g. a fault current can be introduced and it can affect the stability of the micro-grid. Excess power produced by DGs has to be stored or shared with other distribution networks, this corresponds to the power flow management problem and it requires bidirectional power flow with communication.

Therefore, for safe operation in islanding regimes and to maintain power system stability, we need advanced control techniques combined with effective communication techniques that can accomplish this goal. Beyond reliability requirements, this infrastructure should fulfill the characteristics of plug-and-play, dispersion in distributed devices and the need of data information in control schemes. The type of information that has to be sent between different agents can be voltage magnitude and phase, current magnitude and phase, relay status etc.

The information and communication technology (ICT) infrastructure in a micro-grid needs to be reliable, highly available, scalable, secure and easy to manage. The power engineering community, along with their counterparts in ICT, have developed a smart micro-grid conceptual model which consists of three layers: energy and power systems layer, communication layer and information technology layer, as shown in Figure [6].

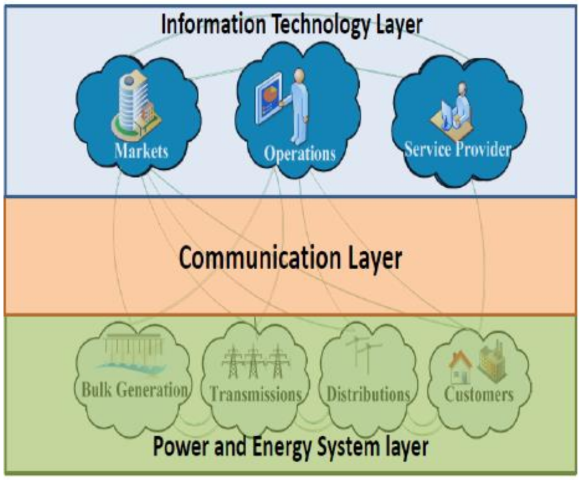

Figure: Smart Grid Conceptual model [6]

V. Micro-grid Building Blocks

Any MG needs two basic blocks to operate successfully:

1) Management System:

The management system includes sensor systems, control algorithms and actuator/physical systems.

Sensor systems include Advanced Metering Infrastructure (AMI), voltage transformers, current transformers and Phasor Measurement Units (PMU) [1]. The AMI provides two-way communications between customers and Meter Data Management System (MDMS) [2]. It is comprised of electronic/digital hardware and software systems that collect data from customer sites through sensors/meters and send it to the service provider by transmitting wired or wirelessly. Other functions include managing data storage, analyzing the required data, providing outage and geographic information and tracking power flow.

The control algorithms portion consists of computing platforms and operational systems that manage the two-way power flow, analyze the received data and compute the desired action [15]. It satisfies the demand response and management for load sharing. This has traditionally been implemented in a centralized cyber infrastructure model referred to as Supervisory Control and Data Acquisition (SCADA) [1]. The system can perform grid optimization, healing and correction of disturbances, switching plans and communication network analysis and management. Physical systems include the principal grid agents, i.e. the distributed energy resources, loads and storage units. Additionally, there are tap changers in transformers, relays and breakers that comprise the actuator system [1].

In summary, the major functions of this block are to perform energy management, transmission operations, distribution operations and regional organization operations [3].

2) Communication infrastructure:

The communication infrastructure may make use of multiple technologies such as wireless, Ethernet, fiber and power line communications [4]. The effectiveness of the communications between the MG components/agents is mostly based on the structure of MG and its control system. Generally, there are two approaches for communication infrastructure in a micro-grid. It can be centralized, i.e. there is a main controller in the MG that collects the required data from agents and performs necessary actions, or it can be decentralized, where every agent has its own controller that will take actions according to their policies. The MG components are mostly controlled using a decentralized decision-making process approach in order to balance demand and supply coming from distributed sources and the main grid [5].

The communication network can be seen as the spinal cord of a MG. They connect the power generating sources, transmission, distribution and consumption systems to the management block in order to evaluate the real-time data that reflects the stability of the entire grid [6]. Information is exchanged bi-directionally among operators, energy generating sources and consumers.

Micro-grid communication networks can be divided into the following categories [6-7]:

1) Home Area Networks (HANs)

This type of network provides low bandwidth, two-way communications between the home appliances and equipment such as smart meters that usually collect the real-time data (power consumption data) from appliances. The exchanged data can be voltage, current, power and frequency ratings, which can be leveraged in demand side management and demand response [6]. This is generally used to inform the customers about their utility usage and requires bandwidth between 10-100 Kbps per device [7]. As there is no need for low latency [7], cost effective and flexible connections are preferred in HANs. Communication technologies that can be used in HANs are Zigbee, Bluetooth and Wi-Fi [6].

2) Field Area Networks (FANs)

This type of network provides two-way communications between the micro-grid control stations and customer premises. Data collected by smart meters in HANs are sent to the micro-grid control center for necessary actions. Control devices in micro-grid stations communicate over this network with electric appliances in consumer premises. A FAN enables monitoring and control of energy distribution networks to enhance the energy delivery [8]. Smart nodes are deployed in consumer premises and control stations for collecting and controlling the data. This network of smart nodes is supported by advanced metering infrastructure, advanced distribution automation and integration of distributed energy sources [7]. Communication technologies that can be used in FAN architectures are RF radio, Wi-Fi, WiMax, PLC/BPLC and GPRS/EDGE [6]. Power line communication (PLC) is a wired technology that has deployment cost comparable to wireless technology as this communication is done through existing transmission lines. Different frequency bands for power line communication are used in transmission and distribution applications in Smart Grid depending upon signal transmission characteristics of the power wiring used [28].

3) Wide Area Networks (WANs)

When a micro-grid is in grid-connected operating mode then a WAN connects it with the main utility grid. It can also work as an external access network that can provide information to external users such as ecosystem operators [6]. WAN schemes are a high-bandwidth, two-way communications implementation for long distances that has effective monitoring and sensing applications. When a micro-grid is connected to the main grid through a point of common coupling, this network is critical for real-time response and safe mode changing. WiMax is a promising candidate for this network due to its vast coverage. A specific communication technology that is suitable for a particular scenario mostly depends on its cost-effectiveness and ability to provide suitable coverage [7]. Some of these wireless technologies will be discussed in the next section.

VI. Wireless Technologies

In the context of micro-grids, wireless technologies are very attractive because they avoid using physical connections in the MG to exchange the information between controllers. One of the most important parameters in wireless technologies is range; the effective distance that can be covered upon implementation. Range determines the physical size, power consumption, cost and type of antenna required. The major advantages offered by wireless communications over wired ones include easy installation of a remote terminal, low installation cost, flexibility to add-on additional devices in future, et cetera. Some of the standard wireless technologies that can be used in micro-grid communication infrastructures in order to fulfill the requirements of various micro-grid applications are:

i) WLAN:

The Wireless Local Area Network (WLAN) is based on the IEEE 802.11 standard that provides robust and high speed point-to-point and point-to-multipoint communication. It links two or more devices using a wireless distribution method (typically spread-spectrum) and providing a connection through an access point to the wider Internet. IEEE 802.11 adopted spread spectrum technology as it can allow multiple users to occupy the same frequency band with minimum interference with other users [9]. The IEEE 802.11 family of standards consists of a series of half-duplex techniques that use the same basic protocol. The most popular are those defined by the 802.11a, 802.11b and 802.11g protocols. IEEE 802.11a operates at 5.8 GHz frequency band with OFDM modulation (Orthogonal Frequency Division Multiplexing). IEEE 802.11b, known as Wi-Fi provides a maximum data rate of 11 Mbps operating at a 2.4GHz frequency band with DSSS modulation technique and IEEE 802.11g operates on 2.4 GHz frequency band with DSSS modulation technique [17]. IEEE 802.11n is based on MIMO technology (Multi-input Multi-output), which increases the data rate up to 600Mbps. WLAN offers benefits over wired LAN in terms of installation, providing mobility and reduced cost.

In a micro-grid, WLAN can be used for various applications. For example, it can be used for distribution substation automation and protection or monitoring and control of distributed energy resources, both scenarios where data requirements and signal interferences are fairly low. Depending on the specific geographical region with dispersed DG units, it may be impossible to deploy wired communication, and thus WLAN is a more feasible alternative.

Reliability on WLAN technology is challenging because it can have interference with electromagnetic waves and can slow down the data transmission. Radio frequency interference from wireless device can affect the power equipment functioning. Wireless communication can be made more reliable by adding data transfer acknowledgments, error correcting algorithms and data buffering in the communication that will enhance the reliability of message transmission over wireless medium. WLAN equipment can be mostly immune to EMI and RFI by using smart antennas that would not affect the functionality of power devices [13].

ii) WiMAX

WiMAX (Worldwide Interoperability for Microwave Access) is a wireless communications standard that was released within the 802.16 series standards with the objective to achieve worldwide interoperability for microwave access. It is a technology known as local loop that allows reception of data by microwave and broadcast by radio waves. There is a relatively low cost associated with the deployment of a WiMAX network compared with other wireless standards. It has two types of spectrum: one is licensed (2.3, 2.5 and 3.5 GHz) and another one unlicensed that operates at the 5.8GHz frequency band and provides data rates up to 70Mbps and distances up to 48km [10]. Licensed spectrums allow higher power and longer distance transmission, which are properties more suitable for long distance communication. The bandwidth and the range of WiMAX provide an alternative for cable, DSL and T1 communication channels for last-mile access.

WiMAX has upper hand in communication infrastructure of micro-grids due to the fact that it can provide long distance coverage and high data rates. It can be used in AMI (Advanced Metering Infrastructure) to provide the main control system for household meters therefore reducing the need for human meter readers. Moreover, it can provide the AMI with real-time pricing models based on real-time energy consumptions of customers, which will be beneficial to facilitate the shifting their loads to off-peak times [11]. Additionally, power outage detection and restoration can be monitored and controlled in a faster fashion through WIMAX.

The disadvantages include the fact that a WiMAX network operated at frequencies above 10GHz can not penetrate through obstacles (e.g. when used in urban area), therefore it can’t be used for AMI applications. Also, a WiMAX tower is relatively expensive so the placement of that tower should be done optimally in order to reduce the need of more towers for a given threshold of QoS (Quality of Service).

iii) ZigBee

ZigBee is a reliable, cost effective and low power personal area wireless network that uses small, low power digital radios based on IEEE 802 standards. It operates at the 868 MHz, 915 MHz and 2.4 GHz frequency bands with DSSS modulation technique providing data rate up to 20-250 Kbps. It provides coverage of 10-10m and with a given data rate, is best suited for periodic/intermittent data or a single signal transmission from a sensor or input device. It supports star, tree and mesh topologies. ZigBee architectures are targeted at applications that require a low data rate, long battery life, and secure networking.

ZigBee has various suitable applications in wireless sensor networks for micro-grids, due to their low power consumption, low cost and low data rate. It can be used to control home appliances by implementing an advanced network consisting of Full Function Nodes (FFN) and Reduced Function Nodes (RFN). The RFNs will function as a network coordinator between appliances and smart meters exchanging the information between home appliances and local HAN (Home Area Network) control. ZigBee end devices can work as a switch when connected with a relay in order to control power supply to home appliances. The HAN can be automatically controlled locally with the help of a controller or remotely using the utility AMI infrastructure [12].

ZigBee devices have low memory and processing capacity and may not be able to handle complex data in micro-grids. They are battery based so they have a limited energy supply. For these reasons, they may not be suitable for critical locations. This technology can perform well in residential automation systems.

iv) LTE

Long Term Evolution (LTE) is a 4G wireless broadband technology providing high speed communication and data transfer with scalable bandwidth. Based on GSM/EGDGE and UMTS/HSPA technologies, LTE uses Single Carrier FDMA (SC-FDMA) for uplink giving peak data rate up to 86.4 Mbps for 20 MHz bandwidth and Orthogonal Frequency Division Multiple Access (OFDMA) for downlink that provides high peak data rate of 326 Mbps with 20MHz bandwidth. Using SC-FDMA for uplink provides 2-6 dB PAR advantage over the OFDMA method used by other technologies such as WiMAX IEEE 802.16e. LTE-Advanced is a further improvement of LTE considered as the next generation technology with wider bandwidth support. In the context of micro-grids, LTE would have great influence on communication infrastructures due to its high peak data rates and scalable bandwidth.

Some other potential wireless technologies include microwave technology and Bluetooth. In microwave transmission, radio waves of small wavelengths are used for transmitting information. It provides long distance coverage up to 60 kilometers. It can be used in point-to-point communication for micro-grid applications (e.g. communication between a DG unit and the corresponding substation). Bluetooth is a wireless technology standard designed to exchange data over short distances. It is part of the IEEE 802.15.1 standard and operates on the 2.4 GHz unlicensed ISM band. It can work in both point-to-point and point-to-multipoint configurations, which can be used for micro-grid local monitoring applications between distances of 10-100m. Bluetooth devices may interfere with IEEE 802.11 based WLAN network and it offers weak security as compared to other standards.

VII. Communication Infrastructure Issues in MGs

QoS

The Quality of Service (QoS) for micro-grids consists of two specific measures: packet loss and latency. These measures have been discussed in Ref. [21] where the authors discuss the wireless technology WiMAX as the most suitable in terms of smart metering capacity and QoS for a Distribution Area Network (DAN). They have done simulations that consider a WiMAX network to cover urban areas that are given power through two substations. Simulation results show that packet loss with bandwidth requirement and latency was within a limit.

A method to calculate bandwidth in distribution networks is proposed in [22] where they consider a distribution system generating 1 million messages over a 100,000-meter network. For example, if messages follow a Poisson distribution and each message is 100bits then the bandwidth need will be of 100Mbps with a latency requirement of 10ms.

In [23], communication protocols DNP3 over TCP/IP are studied in terms of delay constraints. Although TCP/IP is considered as the main micro-grid communication protocol, it can't meet the micro grid applications with delay constraints smaller than 16ms [24]. It has been shown through case studies that DNP3 can be optimized in terms of delay performance in order to meet micro-grid time-critical applications with transport reliability comparable to TCP/IP.

Reliability

Reliability of communication infrastructure depends upon the networking topology, protocols and sensor nodes deployment. Changes in environment can affect the functionality of sensor networks [24]. Various error correcting algorithms are available to improve the quality and reliability of wireless networks.

Security

Security is the most important part of communication infrastructure in a micro-grid. Attack threats usually happen on wireless networking, sensor nodes and communication protocols. The physical and cyber system of micro-grid is a pair of partner networks [28]. The physical portion corresponds to the flow of power from sources to sinks and the cyber network portion is related to the security of the communication infrastructure. The notification of any failure in the physical system is crucial so, security of both physical and cyber network is important for intra-domain and inter-domain communication interfaces for safe operation of the micro-grid. Cyber security alone doesn't guarantee that it will defend against physical attacks as it can only protect the integrity of measurement data by using secure devices and communication protocols. Both cyber and physical networks need additional security requirements such as the continuity of power delivery and accuracy of dynamic pricing [29].

Several standards have been developed to improve the communication security in smart grids such as IEC 62351 and NISTIR 7628-1. These can also be deployed in micro-grids as a natural subset of the Smart Grid concept. In Ref. [4], researchers have used SimpliciTi protocol for communicating wirelessly in micro-grid islanded mode. SimpliciTi is developed by Texas Instruments and based on ZigBee [4]. It is not designed for wide area networks that give limited access and are more difficult to attack on. In terms of security of the network, they have used the XTEA encryption system in which messages are encrypted by the XTEA key, which secures the communication. Ref. [25] presented a method for Smart Grid security by anonymization of smart meter data that may be enforced within the electrical energy distribution network.

Complexity

The micro-grid communication infrastructure is fairly complex due to the fact that different kinds of sensors are deployed across the micro-grid and may not be compatible with standard protocols, thus making it challenging to communicate with each other. Sensor nodes usually have low computation capacity and the handling of complex processes is difficult. Due to the bidirectional communication between agents, a significant amount of information has to be handled by control systems of the micro-grid, which increases the computation costs. Therefore, modeling and designing of communication infrastructure is challenging because it must be capable of accounting for uncertainty and inconsistencies within the micro-grid.

Standardization

Depending upon the application requirements and geographical area/environment, various standards and protocols are good candidates to be deployed in the communication infrastructure of micro-grids. Communication scenarios continuously change when agents have to communicate with each other. For example, smart meters have to communicate with control centers and they require longer range and reliable communication standards than energy storage units when they are communicating with distributed energy resources and are, most likely, next to each other.

IEEE has created a group to help defining these standards known as IEEE P2030 group [27]. This standard will contribute to the design of the devices and agents in the micro-grid in order to effectively communicate with each other. There are some other standards such as ISO/IEC JTC or IEEE 1415 but they are still not sufficiently mature to guarantee effective and reliable communication in MGs. Therefore, there is a vital need for developing and identifying interoperable protocols for different domains in micro-grid design.

Efficiency

The efficiency of communication infrastructure in micro-grids depends upon how well our control systems can handle complex data and give appropriate responses. By applying modern control strategies and communication technologies, we can enhance the monitoring and control capabilities of micro-grids. Similarly, a control center has to process a high number of messages, thus it requires a high performance communication infrastructure that must be capable of fast and reliable delivery of information and commands. In general, efficiency can be improved with fast and robust controls responses, enhancing the computing capabilities of MG control systems and with an effective communication technology that can be selected according to our needs.

VIII. Conclusion

Micro-grids can play an important role in expanding energy access, managing growth in industrializing countries and transforming growth in postindustrial economies. For a micro-grid to operate effectively and successfully we need to choose the best suited communication technique and this is yet to be determined. For any given communication technique, there are several key measures that we need to evaluate, such as reliability, coverage, time delay, flexibility to add devices to the network and transmission error rate. In the context of micro-grids, before we can make such a choice, there are still challenges that are faced particularly with respect to system planning, maintenance level, decision making and lack of adequate predictive real-time system controls.

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