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Wide Area Measurement Systems

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1. Introduction

In last two decades, power industries have been deregulated, restructured and decentralized in order to increase their efficiency, to reduce their operational cost and to free the consumers from their choices of electricity providers (Eshraghnia et al., 2006). As a result of these changes, in comparison with the traditional power systems, new competitive power industries face specific challenges that are related to their generation, operation and planning. As a consequence of these challenges, new intelligent systems should be introduced and established in the power systems in order to tackle such challenges. Wide Area Measurement Systems (WAMS) is a new term, which has been introduced to power system literatures in late 1980s. Recently, they are commercially available in power systems for purposes of monitoring, operation and control.

To be able to monitor, operate and control power systems in wide geographical area, WAMS combines the functions of metering devices (i.e. new and traditional) with the abilities of communication systems (Junce & Zexiang, 2005). The overall capability of this particular combination is that data of the entire system can be obtained at the same time and the same place i.e. the control center. This data, which are obtained from the entire system, can be used by many WAMS functions, effectively. These facts indicate that nowadays, WAMS has been a great opportunity to overcome power systems' challenges related to the restructuring, deregulation and decentralization.

This chapter is allocated to an in-depth survey of WAMS. To carry out this survey, WAMS process is firstly defined and classified into the three main interconnected sub-processes including data acquisition, data transmitting and data processing. These sub-processes are respectively performed by measurement systems, communication systems and WAMS applications.

This chapter is organized as follows. Section 2 provides a basic background and history of WAMS. The definition of the WAMS is given in this section as well. In Section 3, the WAMS process is investigated and divided into three sub-processes. Section 4, 5 and 6 review the pre-mentioned sub-processes, one by one. Finally, this chapter ends with a brief summary and conclusions in Section 7.

2. Background

In this section, a brief background and history of WAMS are provided. Then, the accurate definition of WAMS will be introduced.

2.1 History

Wide Area Measurement System (WAMS) was firstly introduced by Bonneville Power Administration (BPA) in the late 1980s (Taylor, 2006). This was resulted from this fact that the Western System Coordinating Council (WSCC) faced a critical lack of dynamic information throughout the 1980s. As a result of this, in 1990, a general plan to address this problem was formed (Cai et al., 2005). Therefore, the Western Interconnection of the North America power system was the first test-bed for WAMS implementation.

In 1995, the US Department of Energy (DOE) and the Electric Power Research Institute (EPRI) launched the Wide Area Measurement System (WAMS) Project. The aim of this project was to reinforce the Western System Dynamic Information Network called WesDINet. Dynamic information provided by WAMS of WesDINet has been very important and useful for understanding the breakups. This dynamic information can also be used for the purpose of avoiding future disturbances. Furthermore, during deregulation and restructuring process, information resources provided by this WAMS were utilized for maintaining the system reliability (Hauer & Taylor, 1998).

Since 1994, phasor measurement units (PMU) have been used in WAMS and they have provided synchrophasor measurements (Cai et al., 2005). It is noted that a complete survey of PMU will be presented in Section 4. Synchrophasor measurements may contribute previous functions or may introduce some new WAMS functions, which are never achieved previously by conventional measurements. When synchrophasor measurements are used as data resources of a WAMS, such a WAMS will be called PMU based WAMS.

2.2 WAMS definition

There exists a precise and comprehensive definition of WAMS, which has been introduced by Hauer from BPA/Pacific NW National Labs (Taylor, 2006):

"The WAMS effort is a strategic effort to meet critical information needs of the changing power system".

It can be mentioned that a WAMS needs an infrastructure to perform its tasks. This is also defined by Hauer (Taylor, 2006) as follows:

The WAMS infrastructure consists of people, operating practices, negotiated sharing arrangements and all else that are necessary for WAMS facilities to deliver useful information.

In recent years, PMU measurements are commercially available and are widely used in power systems. On the other hand, high speed and low cost communication systems; which are worked based on a layer model, are also well-established in power systems. As a result, the definition of WAMS is slightly different from past. Nowadays, a general definition of WAMS may be presented as follows: The WAMS combines the data provided by synchrophasor and conventional measurements with capability of new communication systems in order to monitor, operate, control and protect power systems in wide geographical area (Junce & Zexiang, 2005).

3. WAMS process

As mentioned at the beginning of this chapter, a WAMS process includes three different interconnected sub-processes (Yan, 2006): data acquisition, data transmitting and data processing. Measurement systems and communication systems together with energy management systems perform these sub-processes, respectively.

In general, a WAMS acquires system data from conventional and new data resources, transmits it through communication system to the control center(s) and processes it. After extracting appropriate information from system data, decisions on operation of power system are made. Occasionally, WAMS may command some actions that are performed by system actuators in remote sites (Shahraeini et al., 2011). All of these facts indicate that WAMS denotes efficient usage of data and data flow to achieve a more secure and a better strategy for the flow of electrical energy. The WAMS process is illustrated in Fig. 1.

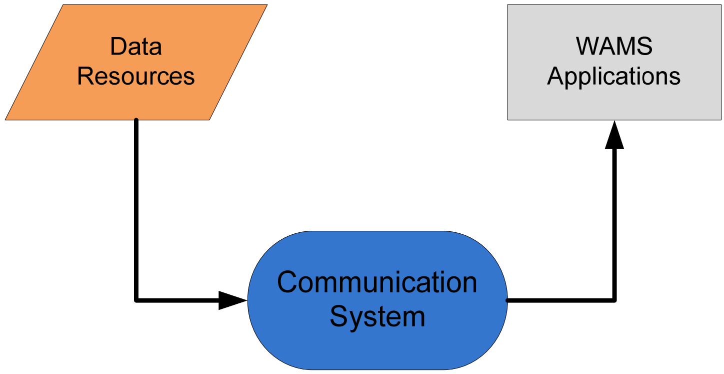

Fig. 1. WAMS Process in Power Systems.

An inspection of the above-mentioned facts together with Fig. 1 indicates that data itself is the fundamental requirement to perform WAMS functions. It can also be concluded that each sub-process has different responsibilities and different tasks that should be performed on system data. Consequently, WAMS main sub-processes should be studied from the data point of view.

In the rest of this chapter, data resources, applications and communication infrastructure of WAMS will be investigated.

4. Data resources of WAMS

Online data and information from the entire system have been essential for secure operation and control of interconnected systems e.g. power systems. In general, system data and information have been provided by data resources of system, which are also called measuring devices (Shahraeini et al., 2010). Data provided by data resources are widely different in terms of their importance, format, volume, sample rate and etc. Thomas et al. (2006) have classified power system data into two main data groups: Operational and Non-Operational data.

The operational data includes the instantaneous measurements of voltages, currents, phasors and breaker statuses that are measured by intelligent devices. Such data is transmitted continuously to the control center(s) through communication systems. Occasionally, they may be used locally for the local decision making.

On the other hand, the non-operational data basically consists of records or logs of multiple events e.g. series of faults, power fluctuations, disturbances and lightning strikes. Typically, the non-operational data is offline data. This means that they are transmitted to the control center(s) either in the specified time intervals (e.g. multiple hours) or when they are requested by the system operator.

There are two main differences between the operational and the non-operational data. The first one is their polling rates. The operational data are normally polled in a regular mode i.e. a continuous stream of data. On the other hand, most of the non-operational data are polled at the defined conditions or they are periodically polled at a specified time intervals. Another major difference is their data format. The operational data is usually transmitted in the form of a stream i.e. stream of numerical variables. While the non-operational data may appear in different formats e.g. waveforms, numerical values, COMTRADE (COMmon format for TRAnsient Data Exchange) format etc. (Thomas et al., 2006).

In this book, the classification of power system data represented by Thomas et al. (2006), is generalized to the data resources of power systems as well. In this section, these two classes of data resources; i.e. operational and non-operational data resources; are summarized in separate subsections. Supervisory Control and Data Acquisition (SCADA) and Synchronized Phasor Measurement System (SPMS) are two operational data resources that will be studied. Alternatively, Digital Fault Recorder (DFR), Digital Protective Relay (DPR) and Circuit Breaker Monitor (CBM) will be investigated as non-operational data resources.

4.1 Supervisory Control and Data Acquisition (SCADA)

SCADA is a generic name for a computerized system, which is capable of gathering and processing data and applying operational controls over long distances. Typical uses of SCADA include power transmission and distribution and pipeline systems (Friedmann, 2003).

In an electrical power system, a SCADA system provides three critical functions in the operation of such a system (Jelatis, 2001):

- Data acquisition
- Supervisory control
- Alarm display and control

In general, a SCADA system consists of both hardware and software. Typically, SCADA hardware may include three parts: Master Terminal Unit (MTU), Remote Terminal Unit (RTU), and Communication System (Stouffer et al., 2008). It should be noted that sometimes Programmable Logic Controllers (PLCs) or Intelligent Electronic Devices (IDEs) may be used as RTU in SCADA systems (Clarke et al., 2004).

The simplest form of SCADA hardware includes: an MTU that located in the control center, one remote field site consisting of either an RTU or a PLC or an IED, and a communication system that provides communication route between remote site and the control center. Fig. 2 shows SCADA sub-systems (Stouffer et al., 2008). Brief descriptions of SCADA sub-systems are as follows:

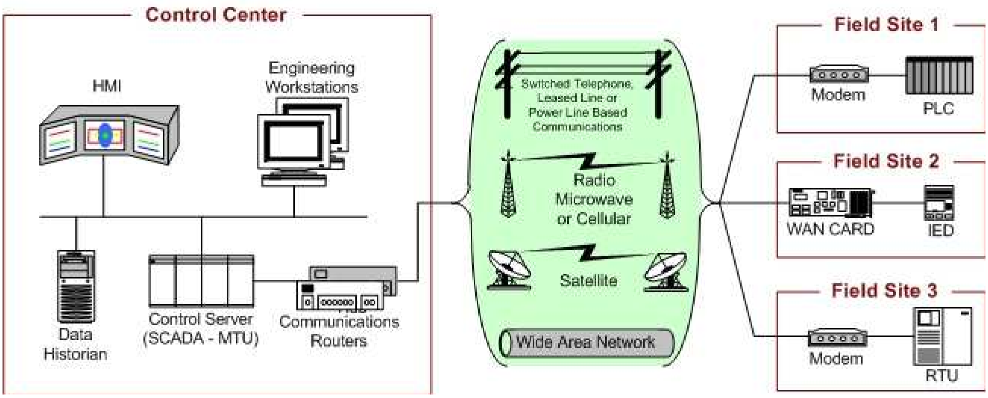

Fig. 2. SCADA sub-systems (Stouffer et al., 2008).

4.1.1 Master Terminal Unit (MTU)

The Master Terminal Unit (sometimes called SCADA center, SCADA server, or master station) may be considered as the heart of a SCADA system. It manages all communications, gathers data of RTUs, stores obtained data and information, sends information to other systems, commands system actuators that are connected to RTUs, and interfaces with operators. Indeed, MTU is a device, which is located in the control center and it acts as master, while RTUs are placed in remote sites and act as slaves (Stouffer et al., 2008).

4.1.2 Remote Terminal Unit (RTU)

The Remote Terminal Unit (RTU) is a stand-alone data acquisition and control unit. RTUs are generally microprocessor based and they monitor and control equipments at remote sites. Their main tasks are twofold: to control and acquire data from process equipments at the remote sites, and to communicate obtained data to a master station (MTU) (Stouffer et al., 2008).

It is useful to mention that traditional RTUs only communicated with a MTU. But nowadays, modern RTUs may also communicate among together. In some cases, an RTU can be configured as a relay. Such an RTU relays data obtained from lower RTUs to an MTU (Clarke et al., 2004).

In general, small-size RTUs include less than 10 to 20 analog and digital signals; medium-size RTUs have 100 digital and 30 to 40 analog inputs. Other RTUs with more inputs are known as large-sized ones (Clarke et al., 2004).

4.1.3 Programmable Logic Controller (PLC)

Programmable Logic Controller (PLC) is a small industrial computer, which is initially designed to perform the logic functions that are carried out by electrical equipments e.g. relays, drum switches, and mechanical timer/counters (Jelatis, 2001). Nowadays, analog control is a standard part of the PLC operation as well (Clarke et al., 2004).

In general, PLCs are modular in nature. They can be expanded to monitor and control additional field devices in remote sites. Since PLCs have built in microprocessor, they can be programmed to function locally even if communication with the master station is lost (Synchrony, 2001).

The PLCs have two main advantages over commercial RTUs. Firstly, they are general-purpose devices and can easily perform variety of different functions. Secondly, PLCs are physically compact and require less space than alternative solutions (Clarke et al., 2004). As a result of these facts, in SCADA systems, PLCs are preferred to special-purpose RTUs because they are more economical, versatile, flexible, and configurable (Stouffer et al., 2008). However, PLCs may not be suitable for specialized requirements e.g. radio telemetry applications (Clarke et al., 2004).

4.1.4 Communication system of SCADA

The communication systems provide communication routes between the master station and the remote sites. This can be done through private transmission media (e.g. fiber optic or leased line) or atmospheric means (wireless or satellite).

There are three main physical communication architectures used in SCADA communications: point-to-point, multipoint and relay station architectures (Clarke et al., 2004).

4.2 Synchronized Phasor Measurement System (SPMS)

The Synchronized Phasor Measurement System (SPMS) was firstly developed and introduced into the power system in mid-1980s. These systems have the ability of measuring currents and voltages, and calculating the angle between them. This ability has been made possible by the availability of Global Positioning System (GPS); on the one hand, and the sampled data processing techniques; on the other hand. In order to synchronize measured angles, SPMS uses time received from GPS as its sampling clock. In addition to measuring angles of voltages and currents, these systems can also measure local frequency and rates of frequency changes, and may be customized to measure harmonics, negative and zero sequence quantities (Phadke & Thorp, 2008).

A SPMS consists of three main parts: Phasor Measurement Unit (PMU), Phasor Data Concentrator (PDC), and communication system. PMUs are normally installed at remote sites. They calculate phasors of voltages and currents and stamp measured phasors with the time received from GPS. A PDC gathers data from several PMUs, rejects bad data, and aligns the time stamps. Communication system of SPMS is responsible for data delivery between PMUs and a PDC or multiple PDCs (Phadke & Thorp, 2008). Fig. 3 shows the hierarchy of SPMS. The next three sub-sections are going to describe each part of SPMS, separately.

4.2.1 Phasor Measurement Unit (PMU)

The Phasor Measurement Unit (PMU) is a microprocessor based device that uses the ability of digital signal processors in order to measure 50/60Hz AC waveforms (voltages and currents) at a typical rate of 48 samples per cycle (2400/2880 samples per second). To do

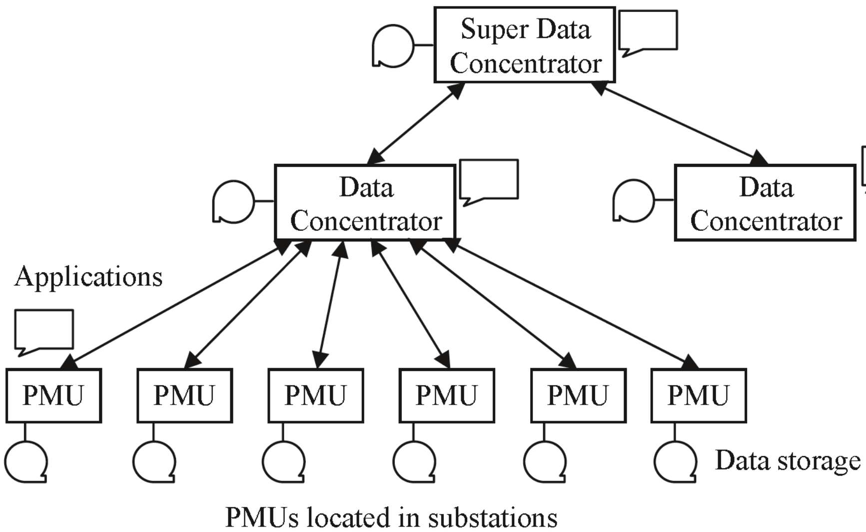

Fig. 3. SPMS sub-systems (Phadke & Thorp, 2008).

this, first, the analog AC waveforms are synchronously sampled by an A/D converter for each phase. In order to provide synchronous clock for the entire system, the time from GPS satellites are used as input for a phase-lock oscillator and thereby, waveforms of the entire system are sampled with 1 microsecond accuracy. In the next step, PMU uses digital signal processing techniques to calculate the voltage and current phasors. Also, line frequencies can be calculated by PMU at each site. By using this technique, a high degree of resolution and accuracy will be achieved. The measured phasors are tagged by GPS time stamps and are transmitted to a PDC at the rates 30-60 samples per second (EPG & CERTS, 2006). Phasor data is formed in COMTRADE format (Phadke & Thorp, 2008).

A study of RTU tasks in SCADA system indicates that PMU and RTU have almost the same tasks in the SPMS and SCADA systems.

4.2.2 Phasor Data Concentrator (PDC)

The main functions of a PDC are: to gather data from several PMUs, to reject bad data, to align the time stamps, and to create a coherent record of simultaneously recorded data. As a consequence, a snap-shot of phasors of the measured area can be obtained (Phadke & Thorp, 2008).

In some cases, a central PDC may concentrate the area data received from other PDCs and may provide phasors of the entire system.

A study of MTU tasks in a SCADA system indicates that the tasks and functions of PDC in SPMS systems are almost the same as those in SCADA systems.

4.2.3 Communication system of SPMS

The communication systems of SPMS may be similar to the SCADA communications in terms of technology, architecture and utilized media. Although these communication systems may be the same, their streamed data are different. The phasor data, which is provided by PMUs, have different nature in comparison with the data of RTUs. Phasor data is continuous and streaming in nature while RTU data is transmitted to the master station either in a specified time intervals or when master station requests it. Another difference between PMU and RTU data is their volume. In general, data of a PMU has more value than data provided by a RTU.

As a result of the above facts, two aspects are of major importance in SPMS communications: communication bandwidth and communication latency (Phadke & Thorp, 2008). High bandwidth communications guarantee that all phasor data can be transmitted to PDCs without any packet drops. On the other hand, low latency communications provide real time streaming between PMUs and PDCs.

4.3 Digital Fault Recorder (DFR)

The Digital Fault Recorder (DFR) acts as the black box of a substation. It records highly accurate waveforms related to faults. The recorded data are huge amount of analog and status data for pre-fault, fault and post-fault conditions (Kezunovic, 2008a). These data may include maximum current, sequence of events, type of fault and the sequence of operation of circuit breakers (Thomas et al., 2006).

The sample rate of the DFR is normally very high and assumed to be 64 to 356 samples per cycle. The DFR data is normally formed in COMTRADE format (IEEE Inc., 2006). Additionally, the data captured by DFRs are offline and they are not used in real time. These data are stored as samples for further offline processing. Generally, the DFRs are installed in the most important substations (Kezunovic, 2008a).

4.4 Digital Protective Relay (DPR)

Historically, different kinds of protective relays have been designed to isolate the area of faults and reduce the impacts of the faults from other parts of the system (Zhang, 2006). The first type of protective relays was electromechanical one. With the introduction of electronic devices e.g. the transistor in the 1950s, electronic protection relays were introduced in the 1960s and 1970s. Recently, digital (microprocessor-based) protective relays have been introduced to the power systems. A DPR uses an advanced microprocessor to analyze voltages and currents of a power system for the purpose of detection of faults in such a system (Hewitson et al., 2004).

Digital protective relays, in addition to performing the traditional relaying tasks, are capable of measuring and recording analog and status data, as well as communicating with a centralized location. They collect current and voltage signals from instrument transformers and digitize them. Due to the fact that relays should act very fast, the accuracy of measured data is not of major concern. Consequently, to speed up A/D conversion, lower sampling rates are normally applied. This implies that data obtained from DPRs are generally less accurate than from the other data resources (Kezunovic, 2008a).

First DPRs sample rates were 4 to 20 samples per cycle, but nowadays, DPRs are available that sample at 64 to 128 samples per cycle (IEEE Inc., 2006).

4.5 Circuit Breaker Monitor (CBM)

The Circuit Breaker Monitor (CBM) is an electronic device that monitors circuit breakers. The CBM captures detailed information about each CB operation in real time; either the operation is initiated manually by the operator or it is initiated automatically by the protection and control equipments (Kezunovic, 2008b). The CBM data is also formed in COMTRADE format.

5. WAMS applications

In general, the information about any system can be extracted from its raw data, which is measured by its data resources. In power systems, this can be achieved by a kind of computer aided tools known as "WAMS Applications" (Shahraeini et al., 2010). Typically, WAMS applications process the raw data measured by data resources and extract usable information for system operator, consumers and customers. Shahraeini et al. (2010) have classified WAMS applications into the three main groups: generation, transmission and distribution applications. Three next sub-sections are going to describe these three groups of applications.

5.1 Generation aplications

Generation applications (GEN): These applications are run in generation level in the way that they acquire and process data of generators in the control center(s). As its consequence, generator information can be obtained in the control center(s) all at once. Generator operation status monitoring and transient angle stability are some examples of such applications (Xiaorong et al., 2006).

In the above mentioned applications, generator status monitoring (GSM) is the most important GEN application since it provides all or part of real time information of generators in the control center. The first kind of GSM was implemented by using DFR as a data recorder (Lee et al., 2000). As DFRs can record the operational and non-operational data with very high sampling rates, they can be used as online recorders in generation sides. If the recorded data is transmitted to the control center in real time, the generator status can be monitored in the control center. After introducing PMUs to the power systems, the information provided by these units can also used for GSM application (Xiaorong et al., 2006). This has been resulted from the fact that PMUs provide phasor data in real time with very high sampling rate (up to 60 samples per second).

5.2 Transmission and Sub-Transmission applications

Transmission and sub-transmission applications (TRAN): In deregulated power industries, some applications are performed at transmission (or sometimes sub-transmission) level by independent system operator (ISO). Historically, these functions are performed by group of computer aided tools called energy management systems (EMS). State estimation (SE), load flow (LF), optimal power flow (OPF), load forecast (LF) and economical dispatch (ED) are some examples of conventional EMS applications (Shahidehpour & Wang, 2003). The aforementioned applications may be considered as conventional WAMS applications since data is fundamental part of all of them.

After introducing phasor measurement units to the power systems, phasor data may contribute conventional WAMS applications or may introduce some new modern WAMS applications. For instance, if a state estimation uses only phasor data as its input, the state equations of the system will be linear. While conventional SEs (that use conventional data) are non-linear and they must use numerical method to solve their equations, iteratively.

Xiaorong et al. (2006) have summarized modern WAMS applications in the power systems. Some of these applications use only phasor data (e.g. Integrated Phasor Data Platform) and some ones may use both phasor and conventional data e.g. hybrid SEs.

Some modern WAMS applications are as follows (Xiaorong et al., 2006): Integrated Phasor Data Platform, Wide-Area Dynamic Monitoring and Analysis, Synchronized Disturbance Record and Replay, Online Low-Frequency Oscillation Analysis, Power Angle Stability Prediction and Alarming, and PMU based State Estimation. Combination of these modern applications with the conventional ones forms a modern EMS in the control center.

In the above mentioned applications, the state estimation is the most important WAMS application and is considered as kernel of EMS (Shahraeini et al., 2011). This has been resulted from the fact that this application extracts creditable data from raw data provided by data resources. Other WAMS applications use obtained creditable data as their input (Shahidehpour & Wang, 2003).

State estimations, based on their utilized data, are classified into the three different types: conventional, PMU based and hybrid state estimations (Shahraeini et al., 2011).

Conventional state estimations use conventional operational data i.e. voltage and current magnitude, active and reactive power flow, and active and reactive power injection.

5.3 Distribution applications

Distribution applications (DIS): In distribution systems, WAMS applications are known as automation applications. According to IEEE definition (Gruenemeyer, 1991), Distribution Automation (DA) systems have been defined as systems that enable a distribution company to monitor, coordinate, and operate distribution components and equipments from remote locations in real time. The DAs aim to reduce costs, to improve service availability, and to provide better consumer services. In general, DA may be classified into three main groups: substation automation, feeder automation, and consumer-side automation (Shahraeini & Alishahi, 2011).

5.3.1 Substation automation

Substation Automation (SA) is the integration of smart sensors with a communication infrastructure to control and monitor substation equipments in real-time (Shahraeini & Alishahi, 2011). The major functions of SA are: service restoration via bus sectionalizing, bus voltage control, substation parallel transformer circulating current control, line drop compensation, and automatic reclosing (Cassel, 1993).

Data resources of SA are located in distribution substations including bus phase voltages, transformer and feeder active and reactive power, feeder currents, statuses of circuit breakers, capacitors and reclosers cut-off switches, load tap changer and voltage regulator positions and statuses, transformer temperatures and relay settings (Cassel, 1993).

Typically, measurement data and status data are measured by pre-mentioned data resources. Then, Remote Terminal Units (RTUs) collect data and send it to SCADA systems. Finally, communication infrastructure has the responsibility of data transmitting from SCADA to the control center(s) (Shahraeini & Alishahi, 2011).

5.3.2 Feeder automation

Nowadays, due to rapid growth in metros, distribution networks have been one of the most extensive infrastructures in metros. In such networks, Feeder Automation (FA) is one of the key elements for efficient management of the power distribution networks. The main purposes of FA are twofold. Firstly, FA aims to automate feeder switching. Secondly, FA controls voltages and active/reactive powers of feeders (Cassel, 1993).

The main data resources and controllable devices of this function are line reclosers, load break switches, sectionalizers, capacitor banks and line regulators. Typically, these data resources are much more than resources of SA and are located at distribution poles (Shahraeini & Alishahi, 2011).

5.3.3 Consumer side automation

Consumer side automation tries to automate the final points of electricity delivery i.e. metering devices of customers. Beyond this, customer equipments may be automated by this application and may be controlled through the control center. Advanced Metering Infrastructure (AMI) and Automatic Meter Reading (AMR) are two main systems utilized to automate consumer sides.

The AMI may be assumed as the central nervous system of the smartgrid architecture in distribution systems. AMI collects consumption data from smart meters and transmits it to the control center. This function of AMI is similar to the purposes of AMR systems. In addition to reading functions, AMI also relays demand signals and pricing information to smart meters in near real-time; and thereby, feedback loop is closed by AMI system (Shahraeini & Alishahi, 2011).

Data resources of AMI /AMR systems are metering devices. But the difference between AMI and AMR is that metering devices of AMI can also be remotely controlled by system operator. Since huge numbers of metering devices are distributed in entire system, the cost of communication system, which is utilized by an AMI/AMR system, is vital. In the view of this fact, low cost communication infrastructure means more automated customers.

6. Communication infrastructure of WAMS

The communication system of WAMS is responsible for data delivery from data resources to the control center(s) and from control center(s) to the system actuators. Indeed, the communication network of WAMS is similar to the neural network of humans. As in case of failure or mal-functioning of neural network paralyzed may happen, failure of communication network may cause huge problems in system operation and control, especially in operation of WAMS applications. Consequently, especial attention should be paid to communication infrastructure, which is as important as electrical infrastructure itself. These two infrastructures (communication and electrical) have become increasingly interdependent so that in the case of failure for each of them, another one may also become out of service (Shahidehpour & Wang, 2003; Lukszo et al., 2010).

New communication systems are designed based on open system interconnection (OSI) layer model. In this architecture, upper layers relay data, assuming that the lower layers work perfectly. In fact, this model is an effective architecture for explanation, designing, implementation, standardization and use of communications networks. The OSI reference model consists of seven layers: physical, data link, network, transport, session, presentation, and application (Shahraeini et al., 2010).

In wide area measurement systems, data resources and WAMS applications normally work at the upper layers of network models. Fig. 4 shows the map between OSI layers and three major blocks of WAMS shown in Fig. 1 i.e. data resources, WAMS applications and communication system (Shahraeini et al., 2010).

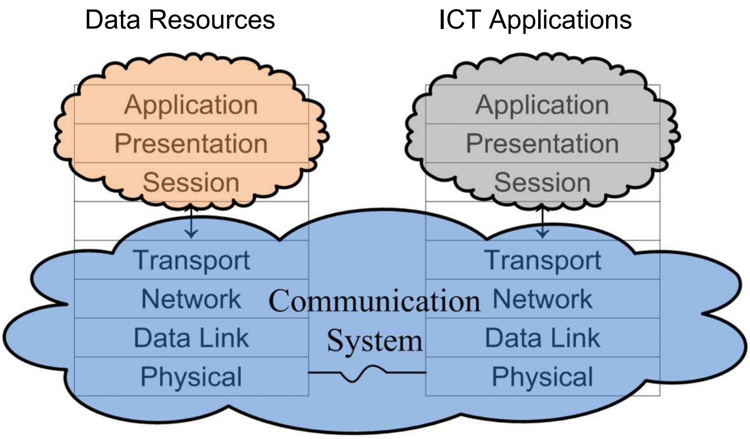

Fig. 4. Layering in WAMS based on OSI reference model (Shahraeini et al., 2010).

The first layer of OSI model, referred to the physical layer, is a kind of medium that establishes the physical connection between transmitter and receiver. The characteristics of the communication systems will become seriously influenced by the characteristics of their media. Therefore, it can be concluded that the characteristics of the transmission media play an important role in communication infrastructure of WAMS. Some major characteristics of a medium are as follows: cost, bandwidth, propagation delay, security and reliability (Shahraeini et al., 2010).

Transmission media, as described below, can be classified as guided and unguided ones (Stallings, 1997). Guided media guides the waves through a solid medium. Twisted pair, coaxial cable, power transmission/distribution line and optical fiber are some examples of guided media. In the case of guided media, the media itself has the most important role in characterizing the limitations of transmission (Stallings, 1997).

On the other hand, unguided media provides a means to transmit electromagnetic waves. However, this media does not guide the signals. The atmosphere and outer space are some examples of this case and usually referred to as wireless communication. Unlike guided media, in the case of unguided media, the signal strength provided by wireless antenna is more important than the media itself (Stallings, 1997). The next sub-sections review these two groups of media.

6.1 Guided media

6.1.1 Power Line Carrier (PLC)

Power line carrier (PLC) has used transmission lines as a medium for communication. This type of transmission media has been one of the first reliable media utilized in power systems for critical communications (Marihart, 2001). This media is also the first guided media commonly utilized in power systems and is a part of power system infrastructure. As a result, failure in power system infrastructure such as line outage causes communication difficulty. PLC systems may be classified as two groups in common, narrow band and broad band PLCs (Shahraeini et al., 2010).

Narrow band PLC usually has low data rates (up to 100kbps). It is used for automation and control applications or few voice channels (Hrasnica et al., 2004). However, due to the fact that the narrowband PLC works in low data rates, this system is very reliable and PLC modems can be installed far from each other (Shahraeini et al., 2010).

Unlike narrowband PLC, broadband PLC establishes a high data rate (beyond 2 Mbps) between two modems (Hrasnica et al., 2004). This kind of communication can be used for multi services such as automation, internet access and telephony at the same time. Broadband PLCs work in high data rates; therefore, distance between two modems is short and modems require more maintenance. This type of communication is not recommended for noisy power lines (Marihart, 2001).

When power lines are used for broadband internet access, power line communication is known as broadband over power line (BPL). BPLs use spread spectrum techniques to deliver data rates previously inaccessible. But because of the fundamental physical constraints, successful data rates will be achieved much above several megabits per second (Nordell, 2008).

6.1.2 Optical fiber

Optical fiber can be used as a medium for communication. Because of its flexibility, fiber optic can be bundled as a cable. As mentioned at the beginning of this section, signals are transmitted through the media by a type of waveform. In fiber cables, the signal is a light wave; either visible or infrared light. Essentially, two types of fiber optic cables including optical power ground wire (OPGW) and all-dielectric self supporting (ADSS) are used in power industries (Shahraeini et al., 2010).

OPGW cable combines the function of grounding and communication. This kind of cable can be used in transmission or distribution lines. In transmission lines, OPGW is replaced with shield wire and is suspended above the lines (Marihart, 2001).

Unlike OPGW, ADSS is a self supporting cable and it does not include any metal component. In fact, they are designed to be fastened into towers or poles underneath the power conductors. Moreover, ADSS is ideal for installation in distribution poles as well as transmission towers, even when live-line installations are required (Marihart, 2001; Nordell, 2008).

6.1.3 Leased line

Historically, leased telephone circuits have been widely used in electric utilities to create a point-to-point or point-to-multipoint communications (Marihart, 2001). The leased lines only provide a share medium for communication and some technologies should be implemented in order to transmit signals through this media. Digital Subscriber Line (DSL) is a group of technologies, which provides digital data transmission over leased telephone circuits. The first version of DSL was defined in 1988 and called ISDN (Integrated Services Digital Network). ISDN provides a maximum of 128 Kbps in both uplink and downlink directions (Hrasnica et al., 2004). Other DSL versions have appeared in different forms, such as high-data-rate DSL (HDSL), single-line DSL (SDSL), asymmetric DSL (ADSL), rate-adaptive DSL (RADSL), and very high-data-rate DSL (VDSL), all of which utilize copper lines. The differences between xDSL technologies are their data rates and directionality of transmission, distances to which those rates can be supported, and the size of the wire.

6.2 Unguided media

Wireless transmission is used when we have several challenges such as environmental or financial limitations for utilization of guided media. However, as transmitted signals using wireless communication can be accessed by anyone, the security of wireless communication is naturally low. On the other hand, various signals, which are transmitted by different sources, may be broadcast on the same frequency and thereby, collision may happen. Thus, it can be concluded that the reliability of wireless communication is less than the reliability of transmission through a guided media. In wireless transmission, signal can take the form of waves in the radio spectrum, including very high frequency (VHF) and microwaves, or it can be light waves including infrared or visible lights such as laser (Shahraeini et al., 2010).

The first important parameter in wireless communication is its range. In accordance with wireless ranges, four wireless types may be defined (Fourty et al., 2005):

- Wireless Personal Area Network (WPAN)
- Wireless Local Area Network (WLAN)
- Wireless Metropolitan Area Network (WMAN)
- Wireless Wide Area Network (WWAN)

6.2.1 Wireless Personal Area Network (WPAN)

Personal networks make a small area networking for a variety of devices. The most popular WPAN has been Bluetooth, which was firstly developed by the Sweden Ericsson. Bluetooth operates in unlicensed 2.4 GHz spectrum, which is also used by Wi-Fi. IEEE 802.15.1 standard for Bluetooth allows data rates up to 3 Mbps and at a range of up to 100 meters.

In addition to the Bluetooth, two industrial technologies, namely UWB (Ultra Wide Band) and Zigbee, make high data rate and low cost WPAN, respectively (Fourty et al., 2005).

UBW, which is standardized under the name IEEE 802.15.3, can use frequencies from 3.1 GHz to 10.6 GHz. UBW allows data rate up to 480 Mbps at the range of several meters and a rate of 110 Mbps at a range of up to 10 meters (Fourty et al., 2005).

Zigbee has been created to become a wireless standard for remote control in industrial fields. It makes very low-cost WPAN for applications that are not too much bandwidth hungry (Fourty et al., 2005). Zigbee allows data rate of 250 Kbps at 2.4 GHz at the range of up to 10 meters (IEEE 802.15.4) and data rate of 20 Kbps at 900 kHz at the range of up to 75 meters (IEEE 802.15.4a). Recently, Zigbee is widely used to create home area communications between smart meters and smart home equipments (Shahraeini et al., 2010).

6.2.2 Wireless Local Area Network (WLAN)

The WLAN technologies connect devices via a wireless distribution method (typically spread-spectrum or OFDM). Wi-Fi is a popular WLAN technology that provides high speed connection on short ranges. In recent years, because of the lack of more suitable metropolitan wireless networks, Wi-Fi has also been used at the metropolitan level. Wi-Fi networks are not suitable for moving devices and they take down in a few kilometers per hour movement. IEEE 802.11 is a set of standards that carry out Wi-Fi (Fourty et al., 2005; Shahraeini et al., 2010). These standards are as follows:

- **IEEE 802.11:** theoretical data rate 2 Mbps - 2.4 GHz unlicensed band (The first standard of the series. It was released in 1997 and clarified in 1999).
- **IEEE 802.11b:** theoretical data rate 11 Mbps - range of 100 meters to a maximum of a few hundred meters - 2.4 GHz unlicensed band.
- **IEEE 802.11a:** theoretical data rate 54 Mbps - range of approximately thirty meters - 5 GHz band.
- **IEEE 802.11g:** theoretical data rate 54 Mbps - range of a hundred meters - 2.4 GHz unlicensed band.
- **IEEE 802.11n:** theoretical data rate 320 Mbps - about thirty meters range - uses two bands 2.4 GHz and 5 GHz.

6.2.3 Wireless Metropolitan Area Network (WMAN)

WiMAX, GPRS, GSM, CDMA and 3G mobile Carrier services are four WMAN technologies, which are used for WMAN communication. The descriptions of these technologies are as follows:

WiMAX: Worldwide Interoperability for Microwave Access (WiMAX) is a communication protocol, which provides fix and fully mobile data networking. WiMAX is based on the IEEE 802.16 standards and its most popular one is 802.16e-2005. Unlike WLAN technologies e.g. Wi-Fi, WiMAX is designed to operate as a WMAN. Various kinds of WiMAX work with both FCC licensed frequencies and unlicensed frequencies. Licensed WiMAX works in the range of 10 to 66 GHz and unlicensed WiMAX works in the range of 2 to 11 GHz. WiMAX theoretical data rate is 70 Mbps with a range of up to a maximum of 50 km with a direct line of sight (LOS). Near line of sight (NLOS) conditions seriously limit their range (Fourty et al., 2005; Shahraeini et al., 2010).

MBWA: Mobile broadband wireless access (MBWA), which is standardized under the name IEEE 802.20, creates mobile metropolitan networks with a speed up to 250 kilometers per hour. It uses licensed frequency band below 3.5 GHz and allows maximal data rates of 1 Mbps for downlink and 300 Kbps for uplink. The maximum range of the cells is 2.5 km. Because of short latency in MBWA technology, this technology is a good choice for mobility data and it can be compared with 3G mobile networks, which focus on the voice (Fourty et al., 2005; Shahraeini et al., 2010).

GPRS: General Packet Radio Service (GPRS or sometimes called 2.5G) is a packet data bearer service for wireless communication over GSM (Global System for Mobile). It applies a packet radio principle to transfer user data packets efficiently between mobile stations and external IP networks. GPRS allows IP-based applications to run on a GSM network (Shahraeini et al., 2010). Using unused channels in the GSM network, it provides moderate speed data transfer. The data speeds can range from 9.6 kbps (using one radio time slot) to 115 kbps (which can be achieved by merging 8 time slots) (Vaishnav et al., 2008).

GSM: It is the most popular second generation standard for mobile telephony systems in the world. There are some differences between GSM and GPRS. GSM is based on circuit-switching technology whereas GPRS makes packet switching network over GSM. GPRS bandwidth is higher than GSM; thus, GPRS has higher data speed toward GSM. In packet switching networks, the bandwidth is used only when a device transmits data. Conversely, connections are "always on" in circuit switching networks. Therefore, GPRS network charges are lower than GSM networks since the billing method is based on data volume and not on call time (Vaishnav et al., 2008).

CDMA: Code Division Multi-Access (CDMA) is another data networking technology for mobile communications. It allows all the users to utilize the entire frequency spectrum for all the time. Multiple simultaneous transmissions are separated by using coding theory. Only users associated with a particular code can understand each other. CDMA can create 64 logical channels whereas 8 channels are available in GPRS (Vaishnav et al., 2008).

3G mobile Carrier services: 3rd Generation networks provide new data carrier services for mobile users. For instance, some networks support High Speed Packet Access (HSPA) data communication with HSDPA standard to provide improved downlink speeds. Furthermore, HSUPA standard is used for uplink speed enhancement. HSDPA provides downlink data rates up to 14.4 Mbps and uplink data rates 384 Kbps. HSUPA provides improved upload data rates of up to 5.76 Mbps (Shahraeini et al., 2010). Another 3G standard for data communication, CDMA2000, allows a maximum theoretical data rate of 2 Mbps (Fourty et al., 2005).

6.2.4 Wireless Wide Area Network (WWAN)

Satellite communications may be used either when a guided media cannot be established between a remote site and the control center or when there is no line-of-sight between such a remote site and pre-installed communication network. Satellites, according to their orbits, may be classified as geostationary, medium, or low earth orbit satellites described below (Fourty et al., 2005):

Geostationary Earth Orbit (GEO) satellites are at an altitude of 35786 kilometers above the equator. GEO rotate around the earth at the same speed of earth rotation; thus, they appear to be fixed from the surface of the earth.

Low Earth Orbit (LEO) satellites rotate between 750 and 1500 kilometers orbit. LEO satellites are widely used for communications. Iridium, Globalstar and Orbcomm are some well-known LEO satellites.

Medium Earth Orbit (MEO) satellites are at altitudes between nearly 10,000 and 20,000 kilometers. From the view point of the earth, MEO rotate slowly in longitude; feel like 6 hours to circle the earth.

These three types of satellites cover surface of the earth almost everywhere, hence; WWAN technologies provide remote sites connections. Although satellites can connect remote sites to the control center, high latency of these connections may create serious problems for some WAMS applications. As a result of this, some critical applications such as WAPS (Wide Area Protection System) should not be implemented under WWAN technologies.

6.3 Comparison of transmission media

To be able to obtain a global comparison among different transmission media used in power system communications, the above mentioned transmission media are compared based on their provided bandwidth, latency and security. This is shown in Table 1.

Media Type	Media	Bandwidth	Latency	Security
Guided	Fiber	High	Low	High
	Power Line	Medium	Low	High
	Leased Line	Medium	Low-Medium	High
Unguided	Wireless			
	WPAN	Low-Medium	Low-Medium	Low
	WLAN	Low-Medium	Medium	Low
	WMAN	Medium	Medium	Low
	WWAN	Low-Medium	High	Low

Table 1. Transmission Media Comparison (Shahraeini et al., 2010).

It should be noted that the above mentioned transmission media may be used either for WAMS communications or for other communications of the system (e.g. SCADA). But the important concept is that the communication infrastructure of WAMS is the most extensive communication infrastructure in a power system. Other communications (e.g. SCADA and SPMS) may be a part of the communication infrastructure of WAMS. Modern communication systems have the ability of physical integration. This means that different communications (e.g. WAMS, SCADA or SPMS) can use the same transmission media and the same routers. In this environment, communication of different applications (e.g. SCADA and SPMS) can virtually be implemented such that communication limitation of each of them is satisfied.

7. Conclusion

Wide Area Measurement Systems (WAMS) is a new opportunity for system operators to monitor, operate, control and protect power systems in wide geographical area. The WAMS combines the data provided by synchrophasor and conventional measurements with the capability of new communication systems in order to obtain dynamic information of the entire system. The WAMS process can be divided into the three interconnected sub-processes; data acquisition, data delivery and data processing. These sub-processes are respectively performed by measurement, communication and energy management sub-systems. Each sub-system has different tasks to perform on system data. As a result, it is definitely important that the functions and the equipments of these sub-systems are deeply investigated from data point of view.

This chapter has extensively reviewed the equipments and the functions of each sub-process, separately. It has been shown that WAMS contributes monitoring systems to shift from the “data acquisition” systems to the “dynamic information” systems. Dynamic information of power systems helps power system operators to overcome generation, operation and planning challenges that may be resulted from system restructuring. Furthermore, it has also been shown that from the big generators to the small home equipments, WAMS systems are capable of monitoring and controlling various functions in real time. It can be concluded that in modern power systems, WAMS is an essential part of power system operation and control.

In particular, this chapter shows that dynamic information of power systems, as a result of WAMS implementation; contributes system operators to make better decisions for system operation and planning. However, in addition to the power systems, dynamic information of any interconnected system (e.g. natural gas pipelines) helps system operators/administrators to reduce operational cost and increase efficiency of such interconnected systems. Consequently, WAMS concepts may be also generalized to other interconnected systems in order to form a dynamic information system and to deliver system data to the related applications in real time.

As a conclusion, it can be stated that although the WAMS was firstly introduced to the power systems in order to obtain dynamic information of such systems, it can also be well established in other critical infrastructures (e.g. natural gas, petroleum, water supply, emergency services, telecommunication and etc.) to operate, monitor and control such infrastructures.

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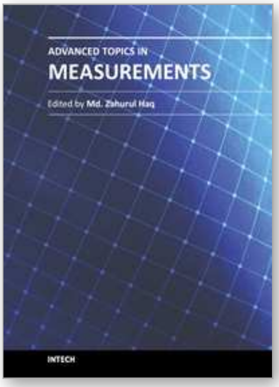

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