ARTIFICIAL INTELLIGENCE-BASED SMART POWER SYSTEMS

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Sivaraman Palanisamy was born in Vellalur, Madurai District, Tamil Nadu, India. He completed schooling in Govt. Higher Secondary School, Vellalur, received his BE in Electrical and Electronics Engineering and ME in Power Systems Engineering from Anna University, Chennai, India, in 2012 and 2014, respectively. He has more than eight years of industrial experience in the field of power system analysis, grid code compliance studies, electric vehicle charging infrastructure, solar PV system, wind power plant, power quality studies, and harmonic assessments. Presently he is working as a Program Manager – EV charging infrastructure at WRI India (major contribution done before joining this position). He is an expert in power system simulation software such as ETAP, PSCAD, DIGSILENT POWER FACTORY, PSSE, and MATLAB. He is a working group member of various IEEE standards such as P2800.2, P2418.5, P1854, and P3001.9. He is an IEEE Senior Member, a Member of CIGRE, Life Member of the Institution of Engineers (India), and The European Energy Center (EEC). He is also a speaker who is well versed on both national and international standards.

Sharmeela Chenniappan holds a BE in Electrical and Electronics Engineering, ME in Power Systems Engineering from Annamalai University, Chidambaram, India, and a PhD in Electrical Engineering from Anna University, Chennai, India, in 1999, 2000, and 2009, respectively. She received her PG Diploma in Electrical Energy Management and Energy Audit from Annamalai University, Chidambaram in 2010. At present, she holds the post of Professor in the Department of EEE, CEG campus, Anna University, Chennai, India. She has more than 21 years of teaching/research experience and has taught various subjects to undergraduate and postgraduate students. She did a number of research projects and consultancy work in renewable energy, Electric Vehicle Charging Infrastructure, power quality, and design of PQ compensators for various industries. She is an IEEE Senior Member, a Fellow of the Institution of Engineers (India), and a Life Member of CBIP, ISTE, and SSI.

Jens Bo Holm-Nielsen currently works as Head of the Esbjerg Energy Section at the Department of Energy Technology, Aalborg University. Through his research, he helped establish the Center for Bioenergy and Green Engineering in 2009 and served as the head of the research group. He has vast experience in the field of biorefinery concepts and biogas production, in particular anaerobic digestion. He has implemented bio-energy systems projects in various provinces in Denmark and European states. He served as the technical advisor for many industries in this field. He has executed many large-scale European Union and United Nation projects in research aspects of bioenergy, biorefinery processes, the full biogas chain, and green engineering. He was a member on invitation with various capacities in committees for over 250 various international conferences and organizer of international conferences, workshops, and training programs in Europe, Central Asia, and China. His focus areas are renewable energy, sustainability, and green jobs for all.

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Introduction to Smart Power Systems

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1.1 Problems in Conventional Power Systems

The conventional power system is generally classified as power generation, power transmission, and power distribution systems. The power is generated from thermal plants, nuclear plants, or hydroplants at remote locations and this is transmitted to the load center through a power transmission system [1]. The distribution system is used to distribute the electric power to various end-users. It has limited control and visibility of power flows from generation to the end user's load. Some of the problems associated with conventional systems are limited visibility in power flows, limited control, delay in measurement and control, higher energy losses in transmission and distribution systems, poor power quality, etc. [2].

1.2 Distributed Generation (DG)

The distributed generation (DG) is used to produce the electric power closer to the load center or end-user loads to reduce the energy loss in the transmission as well as distribution system and improve the voltage profile. The sources of DG can be both renewable energy sources (like solar, wind, and fuel cells), and nonrenewable energy sources (like diesel generators). These sources as simply called distributed energy resources (DERs) [3]. Generally, these DGs are interconnected with the primary or secondary distribution systems based on their rating. Figure 1.1 shows the single-line diagram of a 100 kW rooftop solar PV system as DG connected to the 415 V, 50 Hz secondary distribution system.

Figure 1.2 shows the single-line diagram of a 1 MW rooftop solar PV system as DG connected to the 11 kV, 50 Hz primary distribution system.

The intermittency is one of the major challenges of using renewable energy sources such as solar PV and wind energy conversion systems as DG. Due to intermittence, the output power from the solar PV system and wind energy conversion system also varies throughout the operation resulting in power balance and stability issues [4]. The impact of intermittency can be reduced to a certain extent by using a complex software program/tool to predict the energy output based on various historical data.

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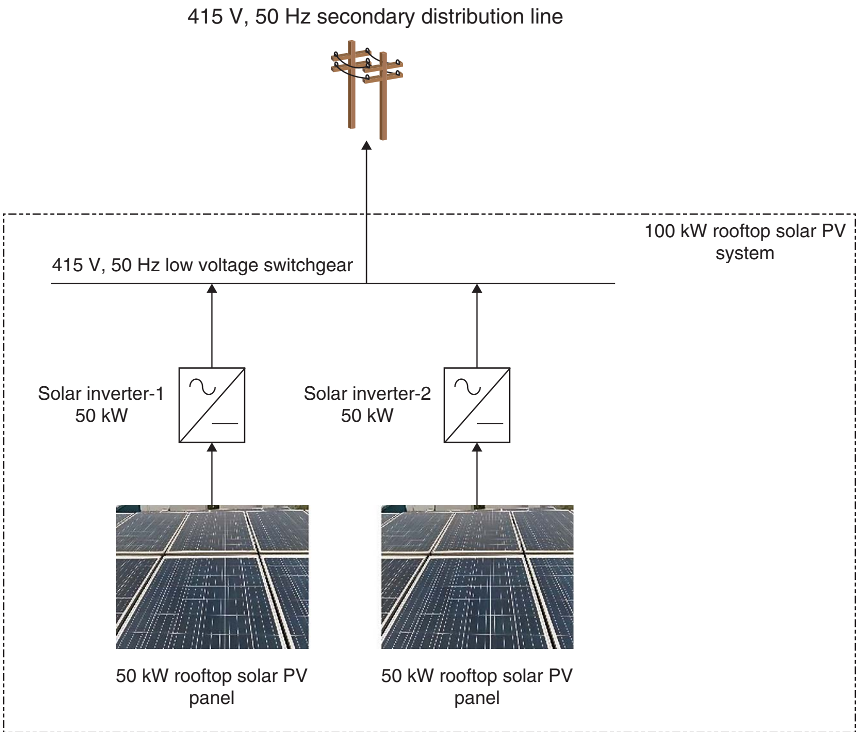

Figure 1.1 Single line diagram of a rooftop solar PV system connected to the secondary distribution system.

1.3 Wide Area Monitoring and Control

Power grids are the most complicated and essential systems in today's life. The risk of experiencing a wide variety of faults and failures is increasing [5]. The unpredictable and cascaded events of faults lead to a blackout, and they have an impact on a large range of consumers. Many grid codes allow the frequency within the specified tolerance limits. Hence, flexibility in frequency leads to under drawl or over drawl of real power, as well as under generation or over a generation by the utilities. This results in the overloading of transmission lines and under voltage or over voltage of the grid. Also, unpredictability, intermittency, and variability of renewable energy integration pose challenges in grid operation. Conventional Supervisory Control and Data Acquisition (SCADA) systems are limited to steady-state measurements and cannot be used for observing the system dynamics behavior. To overcome the drawbacks of a conventional system, one of the most recent advancements in modern power grids is wide-area monitoring (WAM). With the developments of WAM, power system dynamic behavior is monitored closely in real-time. So that the faults in the power grid can be identified and protected in a wider range [6].

The overall goal of using WAM is to improve protection and to develop new protection concepts that will make blackouts less probable and much less severe even if they do occur. The following are the key areas where WAM can help to protect power systems.

1. Dealing with large-scale interruptions
2. Taking the appropriate precautions to mitigate the impact of failed systems
3. Ignoring relay settings that are incompatible with the current system configuration
4. Achieving a reasonable balance between security and dependability

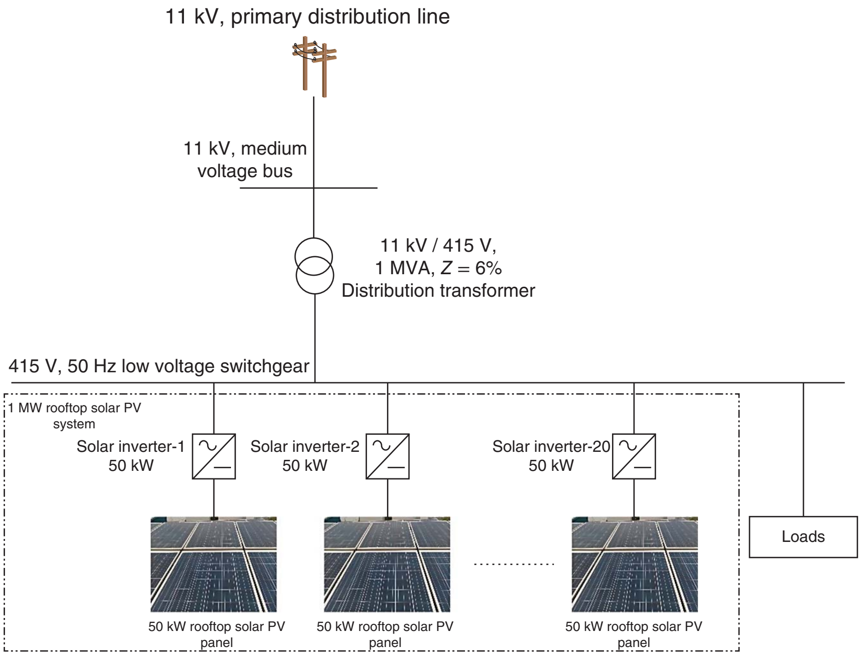

Figure 1.2 Single line diagram of a rooftop solar PV system connected to the primary distribution system.

The purpose of protection is to safeguard specific elements of the power system as well as the security of the power system as a whole.

In the case of main equipment protection, WAM plays a significant role. This is due to the fact that primary protection must consistently offer a very fast response to any failure on the element that it safeguards. WAM, on the other hand, can be a beneficial tool for increasing system performance due to the slower response time necessary for backup protection and the fact that it protects a zone of the system. Wide-area measurements have the potential to enable the development of supervisory methods for backup protection, more complex types of system protection, and altogether new protection concepts. Examples of these protection functions are

1. Dynamic relays adjust their parameters in response to changes in the system condition.
2. Multiterminal line protection has been improved.
3. Predictive end-of-line protection, which monitors the distant location breaker and replaces the under-reaching Zone 1 with an instantaneous characteristic if it is open.
4. Modify relay settings temporarily to prevent malfunction during cold load pickup.
5. Employ the capability of modern relays to self-monitor to find hidden faults and use the IEC 61850 hot-swap capabilities to eliminate them.
6. Artificial controlled microgrids provide an adaptive controlled divergence to prevent an uncontrolled system separation.

WAM gathers data from remote places throughout the power grid and integrates them in real-time into a single snapshot of the power system for a given time. Synchronized measurement technology (SMT) is a crucial component of WAM because it allows measurements to be correctly timestamped, typically using global positioning system (GPS) timing signals. The data may be simply merged with these timestamps, and phase angle measurements can be made with a common reference [7]. Figure 1.3 shows the generic WAMS architecture based on phasor measurement units (PMUs). PMUs, phasor data concentrators (PDCs), communication networks, data storage, and application software are the primary components of WAM. The number of substation PDCs is determined

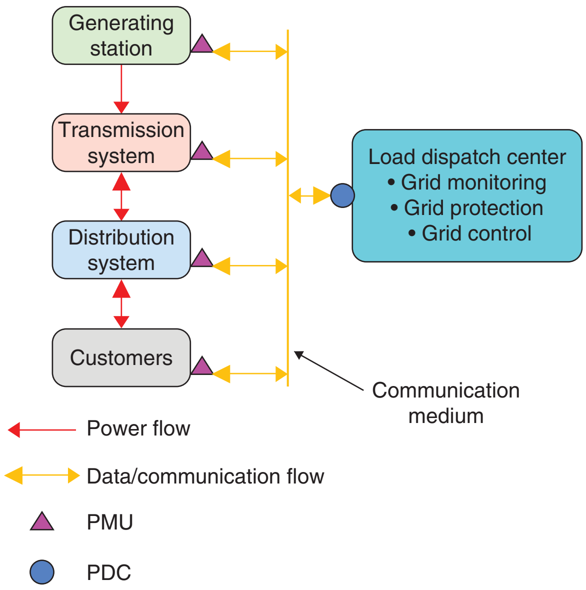

Figure 1.3 Block diagram of wide-area monitoring and control.

by the power system requirements. Voltage, current, and frequency are measured by PMUs placed in substations. These readings are routed straight to the central PDC or a substation PDC.

The following functions are available at the PDC substation:

✓ Synchronization of date and time
✓ Gathers info from PMUs
✓ Analyzes collected data
✓ Data is sent to the central PDC
✓ Communicates data with the regional SCADA
✓ Data is archived locally
✓ Carries out local data analysis and security actions

1.4 Automatic Metering Infrastructure

The name Advanced Metering Infrastructure or simply AMI refers to the entire infrastructure, which includes everything from smart meters to two-way communication networks to control center equipment, as well as all the applications that allow for the gathering and transfer of energy usage data in real-time. The backbone of the smart grid [8] is AMI, which enables two-way connectivity with customers. Error-free meter reading from remote, network problem and its diagnosis, load profile/patterns, energy audits/consumptions, and partial load curtailment in place of load shedding are all potential objectives of AMI. The typical building blocks of AMI are shown in Figure 1.4.

AMI is made up of several hardware and software components that all work together to measure energy consumption and send data about it to utility companies and customers [8]. The key technological components of AMI are,

- **Smart Meters**: Advanced meter devices that could gather data of electrical parameters at various intervals and transfer the data to the utility via fixed communication networks, as well as receiving information from the utility such as pricing signals and relaying it to the consumer [9].

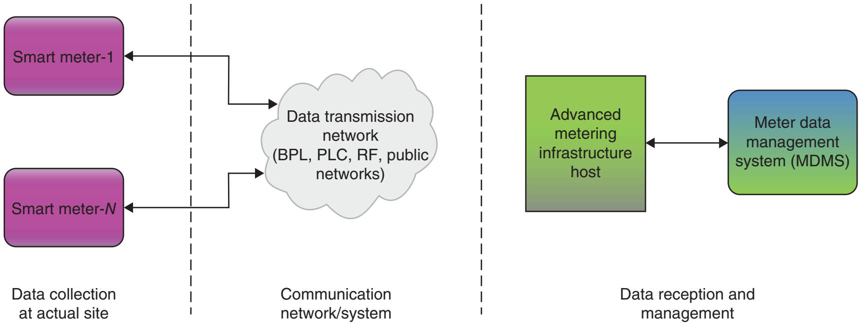

Figure 1.4 Basic building blocks of AMI.

- **Communication Network**: Smart meters can provide data to utility companies and vice versa. The advanced communication networks allow two-way communication between smart meters and utility companies. For these applications, networks like Broadband over Powerline (BPL), Power Line Communications (PLC), Fiber Optic Communication, Fixed Radio Frequency (RF), or public networks (e.g. landline, cellular, paging) are used [10].
- **Meter Data Acquisition System**: Data is collected from smart meters over a communication network and sent to the meter data management system (MDMS) using software applications on the Control Centre hardware and DCUs (Data Concentrator Units).
  MDMS Metering: receives the information, stores it, and analyzed it by the host system.

□ **Home Area Network (HAN)**: It can be a consumer-side extension of AMI, allowing for easier communication between household appliances and AMI, and thus better load control by both the utility and the consumer [11].

The benefits of AMI are multifold and can be generally categorized as follows:

Operational Benefits: The entire system benefits from AMI since it improves meter reading accuracy, detects energy theft, and responds to power outages while removing the need for an on-site meter reading.
Financial Benefits: Utility companies financially benefit from AMI because it lowers equipment and maintenance costs, enables faster restoration of electric service during outages, and streamlines the billing process.
Customer Benefits: Electric customers benefit from AMI because it detects meter faults early, allows for speedier service restoration, and improves billing accuracy and flexibility. AMI also offers time-based tariff choices, which can help consumers save money and better manage their energy usage.
Security Benefits: AMI technology allows for better monitoring of system resources, reducing the risk of cyber-terrorist networks posing a threat to the grid.

In spite of various advantages, AMI deployment faces three significant challenges: higher capital costs or investments, connection or interoperability with other grid systems, and standardization.

High Capital Costs: A full-scale implementation of AMI necessitates investments in all hardware and software components, including smart meters, network infrastructures, and network management software, as well as costs associated with meter installation and maintenance.
Integration: Customer Information Systems (CISs), Geographical Information Systems (GISs), Outage Management Systems (OMSs), Work Management System (WMS), Mobile Workforce Management (MWM), SCADA/DMS, Distribution Automation System (DAS), and other utilities' information technology systems essentially integrated with AMI.
Standardization: Compatibility standards must be created, as they are the keys to properly connecting and sustaining an AMI-based grid system. They set universal requirements for AMI technology, deployment, and general operations.

Investing in AMI to modernize the power grid system will alleviate several grid stresses caused by the rising power demands. AMI will improve three critical aspects of power grid infrastructure such as system reliability, energy cost, and electricity theft.

System Reliability: AMI technology increases electricity distribution and overall dependability by allowing electricity distributors to identify and respond to electric demand automatically, reducing power outages.

Energy Costs: Increased stability and functionality, as well as fewer power outages and streamlined billing operations, will greatly reduce the expenses involved with providing and maintaining the grid, resulting in significantly cheaper electricity bills.

Electricity Theft: Electricity theft is a prevalent problem in Society. AMI systems that track energy usage will aid in monitoring power in real-time, resulting in enhanced system transparency.

1.5 Phasor Measurement Unit

A phasor measurement unit or simply PMU is a crucial measurement tool that is used on electric power systems to improve grid operators' visibility on the huge power grid network/system [12]. It measures the parameter called a phasor and it provides the information/data of magnitude and phase angle of voltage or current at a particular location [13]. This information/data shall be used to find the operating frequency at a particular time instant and examine the condition of the system as shown in Figure 1.5.

A PMU may provide up to 60 measurements per second. As compared with a typical SCADA-based system, the measurements per second are higher in PMU. A typical SCADA-based system will provide the data (one measurement data in two to four seconds time interval) [14]. The main advantage of using PMU over conventional SCADA system is PMU can collect the data of all PMU at a particular time through GPS. This means, that collected data across the power grid are time-synchronized. Because of this reason, PMUs are also called synchro phasors [15].

The information collected from the PMU conveys to the system operator whether the main electrical parameters such as voltage, current, and frequency are within the specified limit with tolerance or not. The capability of the PMU is as follows,

- Line congestion: prediction, analysis, and manage
- Analyzing the event after the disturbance or fault (post fault analysis)
- Instability and stress detection
- Inefficiencies detection

In this decade, several thousands of PMUs are successfully installed and commissioned in transmission and/or distribution grids across the globe. A PMU can be integrated with smart controllers, and this will reduce the manual operations required by the SCADA system in decision making and control. Due to this feature, the grid becomes robust and efficient, it allows the more integration of renewable powers, DERs, and microgrids.

The report on Unified Real-Time Dynamic State Measurement (URTDSM) by Power Grid Corporation of India Ltd. (PGCIL) shows the importance of PMU data (data from various lines at time-stamped) is useful for prediction and post fault event analysis. PGCIL followed the philosophy stated below for installing the PMUs across India, installation of PMUs on substations at 400 kV level above, all generating stations at 220 kV level and above, HVDC terminals, important inter-regional connection points, inter-national connection points, etc. Also, the provision of PDC at all State Load Dispatch Centers (SLDCs), Regional Load Dispatch Centers (RLDCs), and National Load Dispatch Center (NLDC) [7].

The PMU is used to measure the magnitude and phase angle of bus voltage and line current phasor. PMU takes the bus PT input for voltage and line CT input for current at the substation as well as GPS time signal. The PMU presently available in the market can measure one set of bus voltage (three-phase) and two sets of line current (three-phase). The typical arrangement of PMU in substation and Main Phasor Data Concentrator (MPDC)/Sub Phasor Data Concentrator (SPDC) in load dispatch center is shown in Figure 1.6 [7].