IOP Publishing

New Technologies for Smart Grid Operation

Sioe T Mak

Chapter 1

The future of electric power systems

1.1 General introduction

Currently, many electric utility systems generate bulk electric power by converting energy from different fossil fuels or nuclear material into heat, which is subsequently used to generate steam power for operating machines which drive electric generators to produce electric energy. Hydropower is another source used to generate electric power. A network of transmission lines is used to transport the electric energy from the generating plants to population centers and a massive distribution network distributes the energy to users. At the user end, voltages are dropped to a safe level and many different devices convert the electric energy into a form of energy for the immediate use of the customers. During the latter part of the 20th century, wind and solar power conversion devices made their mark as another possible source of electric power.

Electric energy is the life-blood of our global civilization and is here to stay. The demand for electricity continues to increase and much effort is devoted to optimizing its delivery, conversion and use. With an aging energy delivery infrastructure and an increase in demand, much effort is aimed at improving the life, operational reliability and efficiency of existing systems to meet the present and future growth in the number of customers and the associated service requirements. The concept of a smart grid has recently been conceived and promoted by the electric power industry, engineers and various government agencies to enhance the operation and reliability of power generation and delivery to customers. This development has been partially triggered by environmental compliance considerations and also by new concepts of demand response. The demand response concept was at one time equivalent to the load management function which was triggered by the need to reduce peak demand to avoid using standby peaking unit generating plants. Demand response now has a completely different meaning. Customer participation in reducing peak demand, supporting asset management functions to reduce system losses and carbon emissions into the atmosphere, etc, are just a few of the possibilities considered by the

doi:10.1088/978-0-7503-1158-8ch1

industry. In addition, the proliferation of plug-in hybrid electric vehicles (EVs) and the distributed generation of renewable resources coupled with storage capabilities, have started to pose new challenges for system upgrades and operational reliability. The transition to smart grids will be at best evolutionary in order not to disrupt the continuity of service to the customers.

Bulk electric power can be generated at sites away from populated areas, making it more amenable for pollution control, reducing safety and health hazards, etc. Distributed generation (wind power, low head hydro, etc) is being increasingly installed as the price drops and tax incentives are given by governments to encourage the generation of renewable green power.

In many states in the USA, local state governments have started to impose renewable portfolio standards which are primarily driven by measures to limit greenhouse gases, demand response, energy conservation and environmental issues. Electric supply companies are required to provide a minimum percentage of their electricity from approved renewable energy sources. Also, according to the policy statement of the Federal Regulatory Commission, demand response can:

- provide competitive pressure to reduce wholesale power prices;
- increase customer awareness of energy usage;
- provide for more efficient operation of markets;
- mitigate market power;
- enhance reliability;
- in combination with certain new technologies support the integration of renewable energy resources, distributed generation and advanced metering technologies.

In order to obtain a better understanding of how these capabilities can be implemented in economical and gradual comprehensive steps without causing undue interruptions to the energy supply and delivery to customers, the following sections of this chapter provide physical insight into what electric energy is and how current electric power systems operate to deliver this energy to customers.

1.2 The electric energy delivery infrastructure

Electric energy is unique because it cannot be used in its physical form to meet our needs. It is a transitional form of energy which can be easily manipulated and transported. When one mentions ‘electric energy’, one is basically dealing with the generation, transportation, distribution and delivery of energy. Electric energy is the most versatile transitional form of energy with the following desirable basic characteristic features.

It can be transported along narrow corridors in large bulk quantities at practically the speed of light. These narrow transport corridors are the transmission lines, the distribution network, etc. Also, to serve a multitude of energy users scattered over wide geographical areas, multiple independent, parallel and simultaneous energy transport channels are used. These channels form an energy distribution network, which is basically the delivery infrastructure. For an electric distribution network, the major components of the delivery infrastructure are the distribution substation buses from which feeders emanate in different directions and where step-down transformers are used to provide power to the service voltage network. The most common form used today is alternating current (ac) operating at 50 Hz and 60 Hz. This allows the use of transformers to convert the voltage into various levels as required for a safe user level. Direct current (dc) is still used, but only for high voltage bulk power transmission over long distances.

Other unique properties of electric energy are:

- It can easily be split into minute quantities or bulk quantities, depending on the need.
- Conversion into other forms of energy that are useful to people. This is a well-known technology. Conversion into thermal energy is accomplished by using electric resistance wires. Electromechanical conversion devices, such as electric motors, convert the electric power into useful mechanical power. Numerous other applications could be listed.

Most utility networks can still be viewed as having the following major components.

- **Major power conversion plants.** Plant capacities range between a few hundred MW and a few thousand MW. There are now more than 15 000 generators in 10 000 power plants in the USA.
- **A transmission network.** Transmission voltages range between 34.5 kV and 765 kV in the USA. Currently, there are 170 000 miles of high voltage transmission lines rated at voltages higher than 200 kV.
- **A distribution network.** Distribution voltages range between 4.0 kV and 34.5 kV and at the service level voltages range between 120 V and 480 V. With nearly 6 million miles of lower voltage distribution lines, the US grid serves 125 million residential customers, 17.6 million commercial customers and 775 000 industrial customers. At the time of writing, the electric usage by the three groups of customers is, respectively, 37%, 36% and 27% of total generation.

1.3 Delivery network configurations and unique properties of the three-phase network

Three-phase networks operating at 50 Hz or 60 Hz still dominate the existing delivery infrastructure and the circuit configurations can be three-wire, three-wire with grounded neutral return, two-wire or single wire with earth return. The transitions to the various voltage levels are accomplished through the use of three-phase Y–Y with grounded or ungrounded neutrals, D–Y or single-phase transformers. Under steady state operating conditions, the phase to neutral voltages V_{an}, V_{bn} and V_{cn} are quite often transformed into line-to-line voltages on the secondary side by means of three-phase transformer winding configurations. However, when one views each of the phase to neutral voltages at the medium voltage substation bus as base phasors, and the line-to-line voltages as linear combinations of the base phasors, then a unique picture emerges showing some basic characteristic features of the

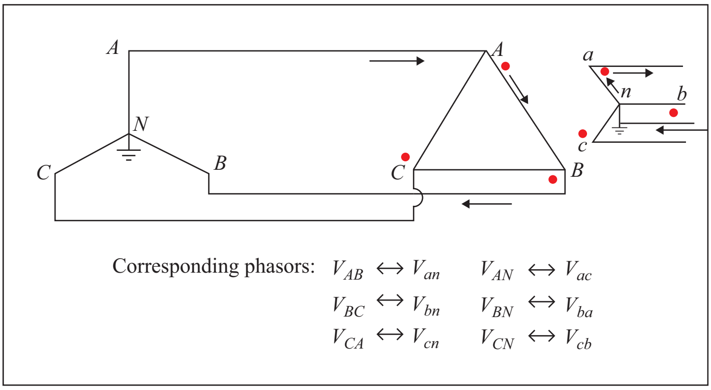

Figure 1.1. Diagram depicting the corresponding phasors rule.

electric network. For any reference phasor generated at the substation bus, there is a remote corresponding phasor at part of the network served by the substation that is slightly phase shifted with respect to the medium voltage substation bus reference phasor. Its magnitude depends on the circuit voltage drop and the intervening transformer winding ratio. A simple example of this is shown in figure 1.1.

Since the voltage is the source of the load current, the load current phasor can also be referenced with respect to the voltage source phasor. If there are no intervening power conditioning devices, one can make this phasor rule connection all the way from the remote customer end to the generator. Any current drawn on the 120 V side has its corresponding phasor on the generation side. Hence, if for any reason a massive cumulative imbalance of load occurs on the distribution side, it will also reflect itself as a massive imbalance on the generation side.

To improve the delivery of energy to customers, a variety of medium voltage and service voltage distribution network configurations are used. For rural areas, radial three-phase feeders served by a medium voltage substation bus prevail in the USA. In metropolitan areas, in particular in downtown areas, an underground low voltage network forms a massive interconnected grid served by a large number of step-down transformers. These transformers are sourced from several medium voltage feeders which obtain their power from a single transmission line or several transmission lines. Open loop medium voltage distribution lines are also common in many metropolitan areas. Most of the distribution transformers in the USA range in capacity between 25 kVA and 500 kVA. In other countries, distribution step-down transformer sizes in the MVA range serving a few hundred customers are not uncommon.

Distribution networks in particular have a unique property. Since there are no distribution circuits that have lengths close to a quarter wavelength of a 50 Hz or 60 Hz wave, no long line or Ferranti effects are expected to occur in the distribution network. This unique behavior of the phasors mentioned above has important implications for the design of control algorithms and applications which will be discussed in the following sections.

1.4 The electric power transient response behavior and energy conversion devices

Another important aspect is the time element, which is intimately linked to the transmitted and observed data. This involves the transient behavior of the network and how it affects the speed of response of a control action. When a switching action takes place, whether due to man-made control actions or naturally induced actions such as a lightning flashover across two conductors or a line fault, the electric network reacts according to some specific patterns.

Energy storage devices such as capacitors (stray capacitances or capacitor banks), inductors, etc, in the distribution network cause a reaction to a sudden change similar to the reaction of a physical system to a perturbation function. In most cases, the reaction in an electric power delivery network is transient oscillatory and decays within a very short time period, in general in less time than the duration of a quarter wavelength of the power frequency. The magnitude also depends on the part of the waveform of the power frequency voltage at which the switching action is initiated and the attenuation, which can be attributed to the energy absorbing parts of the network.

Figure 1.2 shows the transient oscillatory behavior of switching responses extracted from the voltage at the service voltage due to a switching operation at a medium voltage substation bus. A switching device is turned on at a certain angle before the voltage zero crossing of the medium bus phase conductor, causing a current flow into a current limiting load. Subsequently the switch is opened and remains open at a few degrees past the voltage zero crossing. The short duration current loop drawn by the load generates a transient oscillatory current at the feeder phase conductor causing a transient oscillatory voltage drop in the medium voltage feeder phase. This transient oscillatory voltage drop is extracted at the service voltage part of the circuit and is shown in the figure by the darkened waveform. The duration of the oscillatory response is longer than the load current pulse at the medium voltage bus but decays in less than half a cycle of the power voltage.

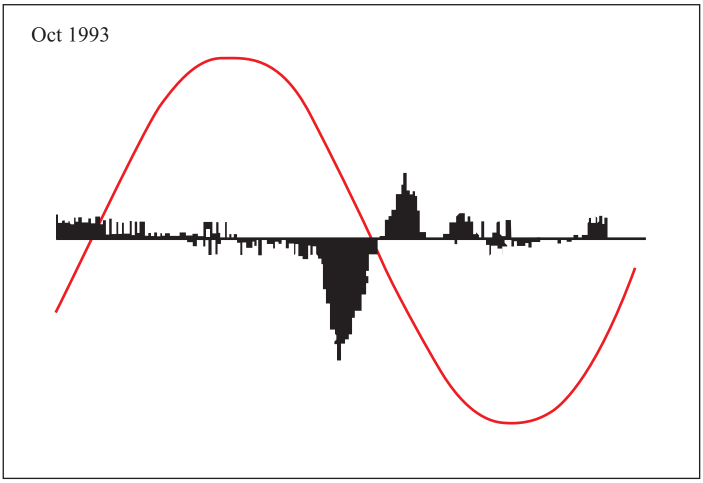

Figure 1.2. Extracted perturbation from field data. Perturbation is introduced at the 25 kV substation bus.

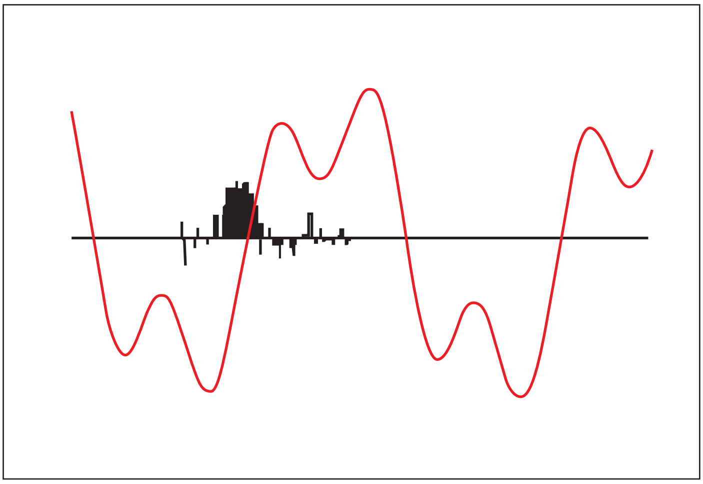

Figure 1.3. Signal captured at the neutral of a WYE distribution substation transformer.

Figure 1.3 shows an extracted current pulse from the neutral current transformer at a substation due to a large single pulsating load at the 240 V service voltage level.

Energy conversion devices such as electric motors, heaters, electric welders, etc, have relatively long transient time constants, with respect to the time it takes for one cycle of the power frequency to reach steady state operating conditions. The time constants typically last for multiple cycles of the 50 Hz or 60 Hz power frequency. An example is the locked rotor starting current of a motor as its output torque gradually increases. Electric ovens and space heaters show similar characteristics before they reach steady state temperatures.

1.5 Advanced metering and smart grid applications

This book primarily deals with electric utility distribution networks and how to use the available tools to optimize network operation and the use of energy by customers. Many of the new applications lend additional support and capabilities to already installed functions.

Lately, there has been a lot of discussion of new applications that will improve the utility network operation and the services to the utility customers. Advanced metering and smart grid functions, made possible by modern digital electronic devices, communication technologies and database technologies, are now being considered in many electric utilities and can be grouped in several main categories. A possible method of categorizing the applications is shown below. This list is by no means exhaustive. It is important to note that many of these functions and applications cannot be viewed or discussed independently without taking into account the synergism amongst them.

1.5.1 Advanced metering and demand response applications

- Electric energy consumption metering.
- New rate structures.

- Remote service connect and disconnect.
- Gas and water consumption metering.
- Load management/demand response.
- Customer services.
- Alarm and customer alarm applications.
- Prevention of unauthorized use of electricity.

1.5.2 Improvement of service reliability and optimization of energy delivery (asset management)

- Outage management and system restoration.
- Feeder load balancing and loss management.
- Integrated voltage and VAR control.
- Power quality monitoring.
- High impedance fault detection.
- Distributed generation integration.
- Hybrid EV and EV charging systems and their demand control.

1.5.3 Supporting functions

- Communication network monitoring and control.
- Extension of supervisory control and data acquisition (SCADA) capability into the distribution network.
- Integration of phasor measuring unit (PMU) technology into smart grid applications.
- AM/FM systems.
- Data management.
- Multi-party users.
- Etc.

1.6 Introduction of the time element

The ability to obtain synchronized, time-stamped interval metering data opens the door for numerous new applications which will benefit electric utilities and their customers. In metering one should also include all energy related data such as voltage, power quality, etc, which the new digital electronics smart meters can deliver. The duration of the monitoring interval depends on the application and the use of the collected information. For a total energy metering device such as a kWh meter, if the reading at time T_1 is P_1 kWh and at the time T_2 the reading is P_2 kWh, then $(P_2 - P_1)$ is the total energy consumed during the interval Δ, where $\Delta = (T_2 - T_1)$. The smaller the time interval Δ is chosen to be, the more accurately one can characterize the load behavior as a function of time. Since P_1 and P_2 both represent integrated values and not instantaneous magnitudes, all fluctuations of the energy consumption as a function of time are absorbed by the integration operation. Hence $\{(P_2 - P_1)/\Delta\}$ represents the average power consumed during the time interval Δ. For load survey and demand metering, the value of Δ is typically 15 min and for advanced billing and novel rate design applications Δ is typically 30 or 60 min.

If a voltage V_1 is read at time T_1, then this is normally assumed to be the rms voltage at T_1. From a mathematical standpoint, the rms value is the result of an integration process to obtain an equivalent dc average voltage for the duration of at least one cycle of the power frequency. The type of information one needs about the behavior of the voltage will determine what is collected, processed and stored within the time interval $\Delta = (T_2 - T_1)$. For voltage profiling of a feeder, the average value of the voltage for the time interval Δ and time stamped when the measurement was performed, is more important than the short time excursions of the peak values of the voltage within the time interval Δ. Time-stamping all of the data obtained, where the start and stop times of sampling (T_1 and T_2) are synchronized, is essential for time correlation of the gathered data with other events that may occur in the distribution network. The information about the energy state of the distribution network in relation to the locations of the energy users in the distribution grid will provide insight into where problems are or might arise. Remedial actions can be taken to prevent damage or nuisance problems in a timely fashion.

In the USA, the National Bureau of Standards cesium atomic clock in Boulder, Colorado, is used for time synchronization. The utility communication network has to broadcast this synchronizing time to all the remote units to set their time. A small variation of a few seconds in the times received by each remote unit, due to communication processing times and propagation delay, can be tolerated.

The hourly time-stamped readings provide sufficient accuracy for apportioning energy usage for billing purposes. A database warehousing all the time-stamped interval metered data is necessary so they can be made available to different interested parties.

In the transmission grid, the situation is completely different. The number of load centers (the transmission substations), ranging in size from a few tens of MW to a few hundred MWs, is small and they are most likely interconnected with each other. The distance between each of these load centers is hundreds of miles. More accurate data on the voltages and currents, correlated to each other in time and by location on the transmission grid, are needed. System operators should quickly be aware of any anomalous system behavior caused by disturbances in order to react accurately and in an expeditious fashion. Coherent real-time information about the voltage, current and other data according to a common time reference is needed. The introduction of satellite communications technology for GPS systems, which also broadcasts time information to Earth, provides a means for time synchronization of voltage, current, etc, monitoring at the various transmission load centers scattered over wide geographical areas. PMUs are now available for obtaining precise grid measurements at high speeds (typically 30 times per second and time-stamped) in a synchronous fashion.

The era of the smart transmission grid has arrived and it is time to integrate this new technology with the smart grid, which was initially conceived for implementation at the distribution level only. The link between the two major grids is the SCADA system, which will play a major role in the integration process. This topic will be discussed in the following chapters of this book.