Chapter 1

Electrical Transmission Systems and Smart Grids, Introduction

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Transmission systems represent the backbone of the electric energy. They support transport of electric energy from large producers (power plants) to the load centers (residential areas, manufacturing facilities, business centers or a combination thereof). Those networks are probably among the largest human-made engineering systems – the transmission network in the United States covers over 300,000 km of lines and is served by 500 companies (electric utilities).

In contemporary power systems, the notion of net energy producers and net users is increasingly blurred as most economic generator capacities are of smaller size and can be (and often are) installed near users' locations – example of small photovoltaic generators or wind farms which can be installed on the roofs of residential homes or in their vicinity illustrates that alternative, popular for many reasons (little or no maintenance needed, decreasing cost of electricity generated by such small generators, many of which are based on various renewable energy sources, reduction of congestion which is the result of carrying large amounts of power across vast distances, reduction of transmission losses, regulatory and policy-driven economic incentives for small owners of generators, reduction of carbon footprint, and enhancement of sustainability of such solutions, etc.) The need for electric energy systems is not only to run the equipment in manufacturing facilities or appliances in residential homes, but also to interact in various ways with other supporting infrastructures (water, gas, transportation, information, etc.) Those infrastructures are interdependent on one another and their efficient and

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reliable operation requires a thorough understanding of those interdependencies and adequate planning and operational support (see Energy and Water Interdependence, and Their Implications for Urban Areas).

As electric energy travels across waveguides (conductors), it incurs losses due to dissipation of current across the resistances of imperfect conductors. High-voltage overhead conductors do not need insulation. The conductor material is nearly always made of an aluminum alloy, which typically forms several strands and often is reinforced with steel strands for mechanical strength. Copper was more popular conductor choice in the past, but substantially lower weight and cost of aluminum and its only marginally inferior electrical performance have been the reasons for the current dominance of aluminum-based conductors in the transmission networks. As large amounts of power being transferred across the lines may incur considerable losses in transmission, typically such bulk transfers are performed at higher voltages, which require smaller currents (losses in the conductors are proportional to the square of the current, which means that operating the transmission line at double the voltage incurs only about 25% of the losses produced while operating at lower voltage). It is the need for changing the operating voltage levels as a function of the energy throughput that has forced design transition from the original DC transmission (introduced by Thomas Edison) into AC, originally deployed by Nikola Tesla and George Westinghouse in the 1880s to transfer power from the power plant at Niagara Falls, and nowadays used almost everywhere. Today, the highest operating AC transmission voltages can be up to 500 kV and even 800 kV. Ironically, when need for high power transfers calls for operation at voltages higher than 800 kV, it is done via DC transmission and with use of the large HVDC converter stations. The reason is inductances of the large overhead transmission lines, which at the highest voltages ultimately choke the efficient transmission of electric energy.

Transmission voltages are usually considered to be 110 kV and above. Lower voltages such as 66 kV and 33 kV are commonly called sub-transmission voltages. Voltages less than 33 kV are mostly used for distribution. Design of distribution networks is driven by their traditional role as infrastructure for disseminating bulk electric energy to a large number of customers. Such fragmentation of delivery requires distribution networks to operate somewhat analogous to capillaries in a cardiovascular system, at smaller capacities (and lower voltages) and covering large areas of sparsely populated customers (in rural areas) or densely populated smaller areas (in modern urban settings where increasingly large part of the world population now resides). Traditional design is evolving of radial distribution network, consisting of feeders supplied from the substations which interconnect them to the bulk power transmission networks. Such simple configurations were enabled by unidirectional flows of energy and simple distribution hardware which was supporting it. Transformation of distribution system into the site of both consumption and (distributed) generation of electric energy, as well as increasing need for enhanced interconnectivity at the distribution level, is imposing need for different designs. Part of the contemporary distribution networks are likely to experience a transition to microgrids (more meshed and better controlled distribution networks which can be used flexibly as reconfigurable autonomous, or grid-connected infrastructure for distribution of electric energy).

The structure and function of electric substations is also changing rapidly. Substations represent a vital part of the power grid infrastructure with many important functions (ability to reconfigure the system topology, isolate equipment for maintenance and repair, monitor and communicate various system parameters and electrical variables to the control center or elsewhere, actuate control actions or protective relaying decisions, etc.) Substation automation represents one of the fastest evolving parts of the modern (smart) grids and will continue its evolution to keep up with the demands for more flexible and effective monitoring, control, and protection of power systems, both on the transmission and distribution side (see Distribution Systems, Substations, and Integration of Distributed Generation).

A growing part of the distribution networks, especially in developed countries, is being served by underground cables instead of overhead lines. There are many reasons in favor of such solutions (reliability, esthetics of the area where underground lines are installed, less vulnerability to the elements, etc.) and some against (considerably higher cost, faster pace of aging, especially due to moisture and impulse electrical stress, such as a consequence of lightning strikes in vicinity of the installations, and lack of effective diagnostic procedures to assess the operational status and effective remaining lifetime of the cables, more expensive repairs, etc.) Nevertheless, underground distribution (and in some places, underground transmission) represent a growing portion of the energy systems' assets, both in terms of importance and cost, and considerable care needs to be paid to their management and upkeep (see Underground Cable Systems).

Distributed generation (DG) can be defined as small-scale, dispersed, decentralized, and on-site electric energy systems. Currently, capacities of DGs vary typically in the range of several kW to hundreds of MW. As more DG penetrates the electric energy systems, more accurate and efficient system analysis algorithms are needed in order to analyze the impact of the DG system on various types of microgrids and distribution networks. Since DG can change the operation of the distribution system and interfere with its protection and control, electric power utilities are not motivated to interconnect customer-owned small generators to their distribution networks. Utilities tend to put nonutility generation under the extensive technical analysis. Conversely, the regulating authorities tend to act in favor of DG owners and support that the interconnection be as easy and transparent as possible. Nevertheless, the favorable economic features of small-scale distributed generators, especially those using the renewable energy resources as input, will make them increasingly popular and much more widespread than they are at the moment of creation of this text. Even now, many countries (Ireland, Spain, Denmark, etc.) possess considerable renewable resources as part of their generation portfolios. At the time when wind generation of electricity is the fastest growing new generation technology (in terms of new installed capacity) and when the energy produced by renewable resources (including hydro plants) is already larger than energy obtained from the nuclear power plants (United States in 2011), engineering challenges of planning, operating, controlling, and protecting the new power grids are substantial and require major transformative changes (see Renewable Generation, Integration of). This may become even more important as some countries elect to gradually abandon conventional nuclear generation and transition to other, more sustainable, generation resources.

One of the fundamental constraints in the transmission and distribution of electricity is that, for the most part, electrical energy cannot be stored, and therefore must be generated whenever needed. Few exceptions to that limitation have been found and exploited. The biggest problem is that currently available storage options cannot effectively be used at utility-scale capacities (pumped hydro plants are the best known among them). In the interim, a large number of smaller capacity storage technologies have been developed and advanced (superconductive magnetic storage, flywheel, battery storage, etc.), mostly to find applications as uninterruptible power supplies for critically important (but relatively small) loads and rarely exceed the capacities needed to achieve similar effects in the bulk power networks. When a storage technology is developed and commercialized to operate at such large capacity levels economically, it will trigger a major revolution in power grid planning and operation.

A very advanced infrastructure of monitoring, control, and protection (see Wide Area Monitoring, Protection and Control) is required to enable real-time balancing between electric generation and energy demand due to the lack of effective storage options. If generation and consumption of electric energy are not in balance or if the complex infrastructure of voltage control across the system is challenged by the heavy loading conditions and/or the aftermath of an unforeseen major disruption in system operation (such as the outage of a major piece of equipment), generation plants and transmission lines can shut down which may lead to a major blackout. Sometimes such blackouts develop spontaneously in a cascading chain of equipment outages caused by spreading of the overloads through the equipment systemwide as a consequence of an initial disturbance, which may be relatively minor in its initial effects. These series of events may occur in unanticipated sequence, and can be hard to foresee even with large computers. An unexpected contingency may cause an amplifying effect of larger sequential outages and progressively stress the system to the point when the disturbance can no longer be contained. In the domain of large power grids, “flapping of the butterfly wings” in certain places can literally produce a “storm” in others (see Transmission Blackouts: Risk, Causes, and Mitigation).

To reduce the risk of such failures, electric transmission networks are highly meshed and interconnected into regional, national, or continental wide networks, providing multiple redundant alternate paths for energy to flow when needed. Considerable effort is expended by electric utility companies to ensure that sufficient spare capacity and redundant pathways for energy transfer are always available to mitigate the consequences of even large multiple disruptions of the network. In order to maintain sufficient security margins under the threat of multiple unpredictable contingencies, well-coordinated plans for preemptive (slower, based on extensive optimization algorithms applied to coordinate generation and control system wide) and preventive (much faster, emergency control and protection) actions need to be developed so that the system does not descend into a blackout and necessitate lengthy and costly restoration procedures (see Smart Grids, Distributed Control for). Particular focus should be on determining the ability of system to survive extreme contingencies, triggered by very unlikely chains of events, but capable of propagating into costly widespread outages with long-term consequences for both consumers and the power companies.

All of the above functional characteristics and solutions describe what is commonly referred to as smart grid. Gradual application of emerging technologies for advanced power grid management and control/protection represents an effective transition to smart grid, which from the perspective of different authors and researchers may assume different characteristics, but in general shares the following functional properties:

- Ability to resiliently recover to the extent possible from the effects of damaging or disruptive disturbances (self-healing)
- Providing opportunities for consumer participation in energy management and demand response (often via advanced metering options which may provide additional support and information, both for the utility and the customer, during normal operation)
- Ability to respond to, cope with, and resiliently enhance itself against physical and cyber attacks
- Providing power quality for modern equipment anticipated to be needed in the future
- Accommodating all generation and storage options
- Enabling new products, services, and markets
- Optimizing assets and operating efficiently

The transition to smart grid may in some cases be spontaneously driven by obvious benefits and cost-effectiveness, in others may be supported by regulatory and policy actions (see Sustainable Smart Grids, Emergence of a Policy Framework).