Research
Smart Grid—Article

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Smart Grid Wide-Area Transmission System Visualization

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ABSTRACT The installation of vast quantities of additional new sensing and communication equipment, in conjunction with building the computing infrastructure to store and manage data gathered by this equipment, has been the first step in the creation of what is generically referred to as the "smart grid" for the electric transmission system. With this enormous capital investment in equipment having been made, attention is now focused on developing methods to analyze and visualize this large data set. The most direct use of this large set of new data will be in data visualization. This paper presents a survey of some visualization techniques that have been deployed by the electric power industry for visualizing data over the past several years. These techniques include pie charts, animation, contouring, time-varying graphs, geographic-based displays, image blending, and data aggregation techniques. The paper then emphasizes a newer concept of using word-sized graphics called sparklines as an extremely effective method of showing large amounts of time-varying data.

KEYWORDS electric power systems, wide-area visualization, power flow, transient stability, smart grid, sparklines

1 Introduction

A reliable electric grid is crucial to the operation of our modern society. Most of the time, electric energy is seamlessly ubiquitous; easily available from the electric outlets that represent the definition of plug-and-play convenience. Yet these outlets are also the gateway to some of the world's largest and most complex machines. Central station electricity got its start in the early 1880s with direct current (DC) systems operating at just 100 V and serving a handful of customers. Over the next century, interconnected electric grids rapidly developed to span countries and sometimes continents with transmission-level voltages up to 1000 kV. Selected by the US National Academy of Engineering as the top technology of the 20th century [1], electrification has changed the world!

However, the grid that developed in the 20th century needs to continue to evolve to meet our new needs as we move forward. This evolution includes the requirements to integrate potentially large amounts of intermittent generation resources such as wind and solar photovoltaics (PVs), and to satisfy the desires of customers for even greater reliability and flexibility. To meet these requirements, the sensing, communication, and computational capabilities of the grid are being rapidly expanded, with these changes generically considered to be part of the "smart grid."

The smart grid is clearly making the grid more intelligent, with much more sensing and embedded automatic control. This intelligence is certainly beneficial, but it also makes the grid even more complex, creating the need for continually improved tools to help humans, who are still very much "in-the-loop," design and operate the smart grid of tomorrow. Over the years, much has been done in power system visualization and analytics with Ref. [2] providing a useful summary circa 2009. The goal of this paper is to provide an overview of power system visualization, touching on both classic techniques that are now widely used in industry and some newer advances that will help the smart grid move forward. In particular, the paper focuses on wide-area visualization, in which the goal is to provide a unified understanding of a large-scale system.

2 Overview of electric grid operations and how the grid can fail

First, it is helpful to briefly describe how the grid operates, and how it can fail. Any electric grid has three major components: the generation that creates the electric energy, the load that consumes it, and the wires that move the electricity from the generators to the load. The wires are typically divided into two groups, the transmission system, typically operating at voltages above 100 kV, and the distribution system operating at voltages below 100 kV. The highest transmission voltages are 1000 kV in China and 765 kV in North America.

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The transmission system is usually networked, which provides for greater reliability by providing multiple paths to each bus (node). In contrast, the distribution system is often radial so that a failure of any component can result in a localized blackout. The electrical equipment at a particular geographic location, including the buses, is called a substation. All large-scale grids are alternating current (AC), with 60 Hz used in North America and parts of South America, and 50 Hz in most of the rest of the world. The high-voltage grid is also three-phase, which allows twice as much electricity to be transported for the same amount of wire compared to a single-phase system; single-phase is usually only used at the low voltages (< 600 V) supplied to end-use customers.

In an interconnected AC grid, all of the generators operate in synchronism (or phase) with one another, meaning that on average they have exactly the same electrical frequency. In North America, there are four major AC interconnections (the Eastern Interconnect (EI), Western Electricity Coordinating Council (WECC), Electric Reliability Council of Texas (ERCOT), and Quebec), whereas there are two in China (the State Grid Corporation of China (SGCC) and the China Southern Power Grid (CSG)). Large-scale interconnections provide two primary benefits: reliability and economics [3]. Since an interconnection can have thousands of generators, reliability is greatly improved because even if the largest generators fail, the lights stay on. From an economic perspective, grid participants can trade electricity anywhere within an interconnection, taking advantage of lower cost generation that may be 1000 km distant. Because the grids operate at high voltages, the total transmission-level losses are usually rather modest, perhaps 3% for the North American EI and 4% for the less dense WECC. Electricity cannot be directly transmitted in AC form between different interconnections. However, such transactions are possible by first converting it to DC, and then inverting it back to AC. These transactions can be done for long-distance power transmission using high-voltage DC (HVDC) lines or at interconnection boundary points using AC-DC-AC conversion.

A key complexity associated with power systems is the wide range of time scales that need to be considered, both operationally and in the development of models, algorithms, and their subsequent visualization. Figure 1 shows some of the key values [4]. For this paper's wide-area visualization focus, the most important time scales are the power flow (quasi-steady-state) and the shorter transient stability. The power flow time frame is how the grid would be perceived if observed in an electric utility control center. That is, while the grid itself is operating at 50 Hz or 60 Hz, the average power flowing on the lines would usually be changing almost imperceptibly slowly in response to the changing system load and generation.

Power flow time scale models come in all different sizes, with 65 000 bus models used to represent the EI in planning studies, and models with potentially tens of thousands of buses in control-center environments. However, to introduce the visualization concepts, it is useful to start with smaller, academic models. Figure 2 shows a visualization of a fictitious seven-bus system using what is known as a "oneline diagram" (or a "oneline"). In a oneline, the actual three-phase devices, such as transmission lines and generators, are shown using a single line. The buses are shown using thicker bars, generators with black circles, the aggregate loads with black pointed lines, and the transmission lines with the thinner lines. The real and reactive power flows are shown for all devices, with the green arrows used to visualize the flow of the real power [5]. As a consequence of Kirchhoff's current law (KCL), at each bus the net real and reactive power must match the generation minus the load at the bus; this is readily verified in the figure. As is common in engineering studies, the voltage magnitudes are shown in per unit (pu), in which the actual voltages are normalized by their nominal values. So in the Figure 2 system, which models a nominal 138 kV system, a pu value of 1.04 corresponds to 143.5 kV. The pie charts on the lines are used to visualize the percent loading in terms of a maximum current limit. These limits are often due to thermal constraints, recognizing that the losses in a wire vary with the square of its current.

The basics of normal grid operation can be thought of as slowly changing power flow solutions based upon the variation in the load, and on manual or automatic changes to the

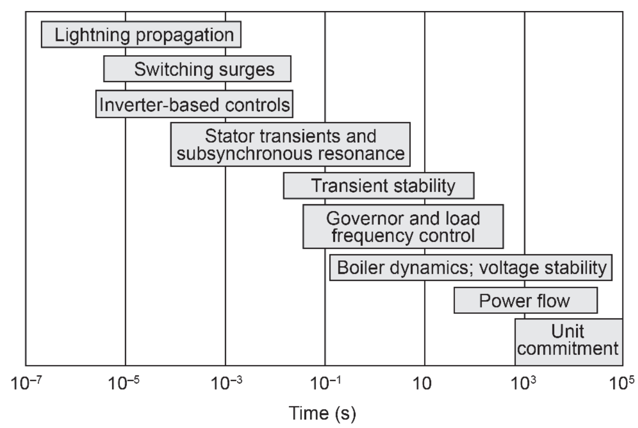

Figure 1. Power system operations time scales.

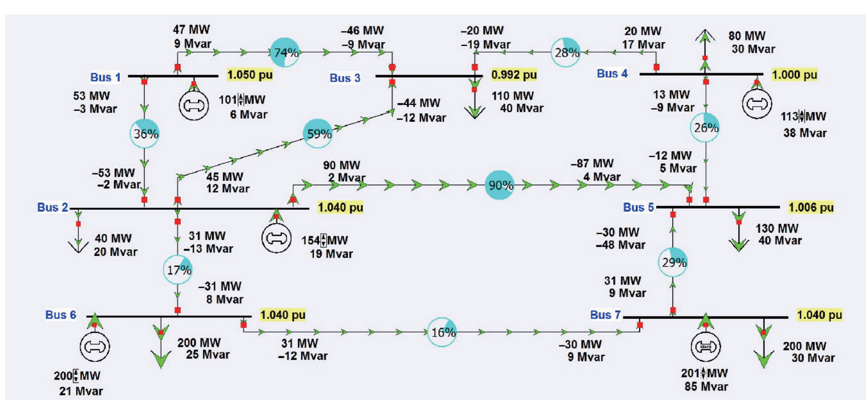

Figure 2. A seven-bus system oneline visualization.