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# Calculating the Grid: A Late 20th Century Story of Innovation, Transition, and Reciprocity in Electrification and Computing

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*Abstract—The National Academy of Engineering classified widespread electrification as the greatest engineering accomplishment of the 20th century. Innovation in computing technologies proved essential to this achievement. Additionally, as engineers adapted computer hardware and software for grid control, they contributed to advances in computation. The traditional story of electrification follows steady expansion from small central station power systems to continental-scale interconnected grids. Yet, transitions triggered by blackouts, evolving energy resource mixes and patterns of use, regulatory restructuring, and technological innovation punctuated this history. System operators faced a consistent challenge—keeping the lights on—as transitions threatened to undermine grid stability and efficiency. Today we are in the midst of another, perhaps more profound, and certainly more rapid transition. Additionally, computation itself poses both challenges and solutions for grid stability. This paper analyzes how 20th-century engineers and system operators developed the algorithms that provide optimization and control of the electric power grid.*

> *"I don't see the power system as just a sandpit for other areas to play in. I believe it's a subject in its own right, with fundamentals, theory, and practice. And just like the communications area or robotics or other areas, we should appreciate everything from theorems to software."—David Hill, Oral History Interview, January 23, 2024*

From the earliest development of central station electrical service, computing devices aided engineers, operators, and managers in their quest to understand what was happening on these complex machines in real time. Pressed to meet demand, at every moment, with sufficient power that was steady, reliable, and at the right voltage and frequency, the owners and operators depended on their ability to process increasing quantities of data more and more quickly [14]. From early mechanical calculators to network analyzers to analog and later digital machines, computing devices and accompanying control instruments supported the analysis that allowed for rapid growth of power systems, and eventually, full dependency on electricity for the vast majority of American economic activity [4], [12], [64], [79].

The intertwined histories of computation and electrification offer compelling examples of advances in one scientific or engineering field influencing innovation in another. The history of electrification documents the explosive growth of power grids over the course of the 20th century [39], [41]. As this process unfolded, system operators, managers, and engineers encountered unanticipated complexities of electricity


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behavior on alternating current, interconnected systems [14]. Across much the same time period, computing machines evolved from hand-operated mechanical instruments to electrified analog models to increasingly sophisticated digital machines. These tools, and the accompanying methods of computation, facilitated efforts to make the power grid more legible, controllable, and reliable. Whether the motive was profit on the part of electric utility owners, access on the part of public interest groups and economic sectors, or equity and fair return on the part of regulators, growth was the bottom line. As Rebecca Slayton argues, as the industry began restructuring in the 1980s and 1990s, adoption of advancing information technologies not only facilitated the shift away from regulated monopoly control of power systems, but also introduced new challenges for safe and efficient operations [73]. Yet, without computation technologies and techniques, building a stable and reliable interconnected power system would have been impossible.

This paper traces the intersections between power systems and computation advances across the latter decades of the 20th century and into the early 21st century. It draws upon the results of the *Algorithms and Power Systems Architecture project*, funded by the Alfred P. Sloan Foundation in 2023. Through this project, the authors and their team interviewed 41 engineers who made significant contributions to the control, stability, and optimization of electric power grids in the last decades of the 20th century [21]. Interestingly, the interviewees frequently pointed to limitations of older computing technologies that hindered their efforts or programming and algorithmic interventions that increased computing functionality for solving power system problems, and advances in hardware and software that spurred innovation in electrification. These reflections triggered the team's interest in better understanding the computation/electrification nexus across the longer history of both industries.

The aggregate stories of these power system engineers revealed a process that was recursive. As engineers addressed an emerging problem on a power system, they adopted, adapted, or influenced the development of the computing tools. At the same time, the new tools deepened understanding of how the power system behaved and what kinds of problems could be addressed more thoroughly. Events affecting the broader population, such as blackouts, economic turns in adjacent energy sectors, and regulatory evolution, often triggered a new cycle of innovation and cross-pollination for the power and computing industries.

As engineer David Hill notes in the opening quote, the power system is not only an essential component of our built environment, but also the locus of "fundamentals, theory, and practice."[1] (Hill, 00:03:38) In his 2022 IEEE CSS Hendrik W. Bode Lecture, Hill explained that power system experts made theoretical contributions that led to real-world improvements [43]. The physical characteristics of alternating current on interconnected systems, in turn, presented new scientific and engineering problems to be explored.

While the history of computing encompasses an abundance of work examining the development of computer technologies, and the growing field of energy history covers a wide range of topics from primary resource extraction and conversion to end use, very few scholars focus on the intersection of computation and electrification. Vannevar Bush at MIT developed the network analyzer explicitly to calculate power network problems, and historians have looked for the roots of his ideas in earlier approaches to calculating machines [64], [65], [79]. Bush collaborated with General Electric to make the analyzer useful to utilities, and other electrical manufacturers followed suit, in turn influencing the business framework of the computer industry [4], [58], [81], [83]. Indeed, with the advent of time-sharing, the computer industry was often described as a utility itself, erroneously as some have argued [30], [49]. Several historians acknowledge the fundamental role played by computing technologies to further the development of power systems, in replacing limited physical models of new infrastructure [48], in facilitating advances in system maintenance [67], and in supporting intersecting approaches to cost recovery and operating efficiency by both engineers and economists [9]. One of this paper's authors, Cohn, detailed the relatively slow adoption of digital machines on the part of utilities [12] and the industry's reliance on data gathering and computing technologies to achieve conservation goals [13]. Interestingly, in recent years, scholars have turned additional attention to the technologies and practices of system control mediated by computers, underscoring the tensions in electric power systems between reliability and economy [71] and technical best practices [5]. The following sections of this paper introduce the reflections of power systems engineers on the role of computing in their work, and

[1]Transcriptions of the oral history interview are cited throughout the paper. To minimize duplication, the interviewee name and timestamp for quoted material will be provided in parentheses. Date and location of the interviews are included in the appendix. The transcripts will be accessible through the University of Houston Special Collections once the archiving process is complete. https://libraries.uh.edu/special-collections

illustrate the essential role of computational advances for power system growth.

The remainder of this paper is organized as follows: The first section will give a brief overview of the grid as a mesoscale infrastructure and historical links between electrification and computation. The second section will describe the oral history project, the data it generated, and a few of the overall analytical findings. The third section will examine several key episodes of innovation, indicating how they were framed by major events or trends, and illustrating the recursive relationship between power systems engineering and computing advances. The paper will close with reflections on these stories about the co-constitution of grids and computing, and interviewees' ruminations on the future grid.

## The Mesoscale Grid: A Heritage System of Machines, Wires, and Algorithms

The term *grid* connotes a variety of physical objects and theoretical concepts, including a system of intersecting lines, graph paper, football fields, city street layouts, and power networks. In the case of power networks, *the grid*, while not adhering to a technical definition, typically refers to a collection of generators, transmission lines, transformers, and distribution lines: a set of objects that converts energy resources into usable electricity and delivers it to a customer's meter. Indeed, the term often encompasses these objects as a single entity despite the fact that they are not all connected. There are four major interconnections in North America, for example, and numerous small electric power networks. Yet, taken together, these are often called *the grid*. And it is without question the case that power systems are human-built; first deployed in the late nineteenth century on a small scale and now undergirding the vast majority of all human social and economic transactions. One might describe the grid as the mesoscale built infrastructure that supports and facilitates each of the other human-built environments prevalent in 21st century life.

Today's power grid looks somewhat different from the first central station systems that amazed urban dwellers in the 1880s [56]. For example, Thomas Edison's Pearl Street central station provided electricity to illuminate the streets of a square-mile quadrant of downtown Manhattan [41]. The system operators of companies like Edison's, known as *load dispatchers*, had only a few thousand customers with a limited number of uses for electricity for whom they kept their networks going. North America's four major interconnections today provide electricity to hundreds of millions of customers in three countries for everything from kitchen appliances to complex and delicate medical devices to enormous data centers. The US portion of the system includes approximately 500,000 miles of transmission lines, 5.5 million miles of distribution lines, and more than 12,500 utility-scale generators, plus thousands of smaller installations, delivering more than 4.3 million gigawatt-hours of electricity annually [1], [26]–[28], [54]. While thousands of public and private entities own and operate segments of the US grid, several independent system operators and regional transmission organizations operate the transmission networks. It is the job of these system operators to keep lights on and machines running.

For electricity to be usable, it must be available at the instant of demand, at the right frequency and voltage, and without interruption: a set of conditions that were challenging for system operators from the early days of electrification [17]. With mechanical devices, telephones, hand-drawn charts, and their own experience, operators maintained system stability. As they interconnected with neighboring systems, the job grew more complicated. The quantity of data needed to understand how these expanding networks functioned grew apace. By the early 20th century, power system experts turned to recording, calculating, and controlling devices to help with data collection and analysis. Inventors and manufacturers began to offer purpose-made apparatus, such as electric clocks and specialty slide rules, and later, network analyzers, to meet the needs of the power industry [4], [79]. In turn, power companies proved to be early adopters of newfangled computing and calculating machines to help with system planning, design, operation, and control. In other words, the power and computing industries evolved in tandem through the early decades of the 20th century.

Despite deep familiarity with specialty computing apparatus, however, power systems engineers were not necessarily engaged in computing as its own effort. In 1946, the American Institute for Electrical Engineers (AIEE) tapped Charles Concordia from General Electric to form the Subcommittee on Large-Scale Computing Devices [19], the predecessor to today's IEEE Computer Society. Concordia recalled thirty years later, "I had some difficulty in assembling a subcommittee, for there were not then a great many AIEE members familiar with the field" (p. 42). Yet, in 1947, 350 conference-goers attended the first session organized by Concordia's group. Individuals in the power industry continued to track the evolving use of computers for their quotidian duties, and organized the Power Industry Computer Applications (PICA) conference in the United States in the late 1950s and the Europe-based Power Systems Computation Conference (PSCC) in 1962.

By the mid-century, engineers found a multiplicity of uses for both analog and digital machines [16], [32], [33]. In 1965, computers aided in automatic load and frequency control, calculation of generator incremental costs, load forecasting, computation of economic load distribution, calculation of available spinning reserves, and determination of optimum power exchange between interconnected systems; in sum, optimizing operation of generating stations on interconnected networks while maintaining system stability. Industry engineer Nathan Cohn noted that control theory had displaced empirical experiments, stating "Simulation in particular, using both analog and digital computers, has been helpful in dynamic modeling, in the development of advanced control concepts, and in the synthesis of multi-variable control systems." [16, p. 69]. Utility engineer Tomas Dy Liacco explained that computers aided in both generation control and supervisory control by the late 1960s [25]. He observed, however, a transition underway toward analyzing the entire operation from a systems perspective. This evolution coincided with the emergence of much higher-powered supercomputers [18].

With faster computers, more memory, the ability to run multiple programs simultaneously, and the falling cost of computer equipment, power companies and system operators assigned additional tasks to these machines. System security analyses [75], [82], state estimation [53], and various generator dispatch tasks [3], [51], [52], [60] all joined the computation repertoire by the end of the 20th century and were improved during the start of the 21st century. The participants in our oral history project reflected on their own contributions to power systems optimization, stability, and control, and in the process, pinpointed significant moments of insight that hinged on the intersection of industry needs and new computing capabilities.

## Asking the Experts: The Oral History Project

Much as today's grid differs from the central station service of Thomas Edison's day, different energy resources and technologies promise to transform the power system tomorrow. A team of historians and engineers pondered how the power industry coalesced around standardized algorithms for system control and optimization in the past, and whether these approaches would be appropriate or sufficient for an evolving grid. These questions arose out of the observation that the rise of wind and solar generation and batteries is changing the physics of grids in ways that are not yet fully understood at a system-wide scale [72].

For more than a century, giant spinning turbines produced physical signals used by system operators to control frequency and voltage. Wind turbines, solar arrays, and batteries connect to the grid using power electronics, called inverters, that can be programmed in multiple ways to mimic, respond to, or perhaps direct grid dynamics [77]. While newly minted engineers often treat the standardized algorithms for optimization and control as laws of nature, history illustrates that reaching consensus around a technical standard could be fraught, and was almost always framed by the the broader context in which the issue evolved (see, e.g., [22]).

The project team understood the value of looking back to answer how the industry converged around standards. The question regarding control of a future renewables-rich grid encouraged a glance ahead as well. The team agreed that interviews with key contributors to grid control and optimization of the late 20th century could allow us to invite reflections on how we reached our standardized approaches and elicit forecasts for addressing the current and coming challenges. As Donald Ritchie explains [66, p. 318], "oral history collects memories and personal commentaries of historical significance through recorded interviews." While not considered objective, oral histories provide both meaning and interpretation on the part of the narrators, which is especially helpful when examining the complex and fast-paced histories of electrification and computing [63]. The resulting project included three elements:

- oral history interviews with power system experts active in the latter decades of the 20th century;
- examination of the influences that led to key papers in power systems control and optimization; and
- development of the historical context in which standardized algorithms emerged.

The team interviewed 41 power systems experts whose contributions date back to the mid-1960s, many of whom are still active in the field today.[2] For each oral history, at least one historian and one engineer participated to ensure that the interview process met with best practices and also addressed relevant technical topics. Often the interview took place with an additional audience of interested engineering colleagues and

[2]Table 2 provides a list of interviewees in the appendix.

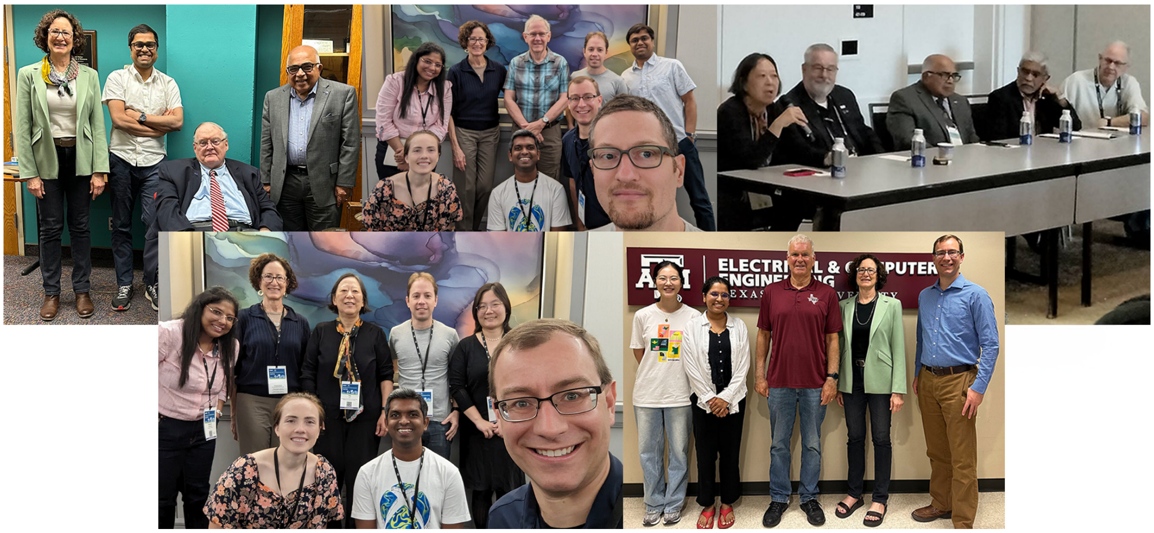

**FIGURE 1.** Photos from selected oral history interviews and panel discussion. From left to right, Upper-left photo: J. Cohn, S. Dhople, B. Wollenberg, and A. Bose; upper-middle photo back row: S. Chatterjee, J. Cohn, I. Hiskens, B. Johnson, S. Dhople; upper-middle photo front row: R. Harris, M. Bhuiyan, D. Gross; upper right photo: Y. Liu, M. Lauby, A. Bose, V. Vittal, I. Hiskens; lower left photo back row: S. Chatterjee, J. Cohn, Y. Liu, B. Johnson, T. Jung; lower left photo front row: R. Harris, M. Bhuiyan, D. Molzahn; lower right photo: S. Kang, S. Kunkolienkar, T. Overbye, J. Cohn, D. Molzahn

graduate students. Figure 1 shows selected photos of the interviewees, project team, and other audience members. Forty interviewees agreed to have their interviews recorded and archived. Eleven interviews took place online, while the remainder were conducted in person, several during the 2023 and 2024 IEEE Power and Energy Society General Meetings. The recorded interviews and accompanying transcripts will be archived at the University of Houston Libraries Special Collections.

The interviews covered a wide range of topics, beginning with the interviewee's educational and professional backgrounds, and focusing on both significant technical challenges the interviewees faced and contributions they considered of great importance. Key topics that emerged included computation of power flow, state estimation, system security, optimization, market design, outage investigation, data collection and analysis, and time synchronization. With very few exceptions, the interviewees pointed to advances in computation, computer hardware, or computer software that proved essential to their work. In addition, interviewees mentioned significant events that established the context in which their work took place, including major system failures, perceived energy shortages, regulatory changes, Congressional actions, industry restructuring, and definition of various environmental concerns.

Those who joined the power systems field as professionals in the 1960s and 1970s indicated that much of their work was heavily influenced by the aftermath of the 1965 Northeast Blackout and additional major power outages that followed. They pursued better modeling and analysis of power systems in order to prevent future major outages, development and deployment of effective tools to respond quickly to potential system failures, and analysis of blackout events. Engineers who initially joined the profession in the 1980's often focused on stability and voltage control, in response to unprecedented voltage collapse events in multiple locations around the world. By the 1990's, the move to restructure the vertically integrated monopoly utilities into their component parts of generation, transmission, and distribution framed heightened interest in optimization of grid operations, the design of markets, and mitigation of the mismatch between financial transactions for power and the physical laws that govern grid dynamics. Throughout all of these years, accuracy and consistency of time-synchronized measurements across devices became a pressing concern, a problem resolved in the early 2000s with satellite clocks integrated into system monitoring and measuring devices. In these first decades of the 21st century, many of the interviewees continue their work with attention to the integration of inverter-based resources and the development of distributed generation.

Leveraging insights gained from the oral history interviews, the next section describes key power system innovations alongside their relationships to computing technologies.

## Keeping the Lights On: How Engineers Used Algorithms and Computing Innovations to Tackle Blackouts, Energy Crises, and Industry Restructuring

The oral histories revealed key topics at the intersection of power engineering and computation, four of which are detailed next. Table 1 provides technical background on each of these topics along with references for further information.

### Algorithms, Blackouts, and Computing Power: 1930-1970

When the lights go out today, customers question the reliability of power systems. Loss of electrical service was somewhat commonplace in the late 1800s, less so in the early 1900s, but still not a surprise as late as the 1930s. By the 1950s, Americans expected continuous access to electricity at the right frequency and voltage, for as long as needed [57]. Indeed, power system experts downplayed the likelihood of major cascading power failures. Nonetheless, they invested in techniques for modeling power flows in order to better plan for expansions and interconnections, predict system behavior, and operate more efficiently.

First deployed in the 1930s, network analyzers provided scale models of power networks to simulate various combinations of generation and load. Experimentation with both analog and digital solutions continued through the 1940s and 1950s [24], [34], [40]. In addition to computational speed, debates on tradeoffs between analog and digital solutions notably included nontechnical aspects. For instance, a discussor of [24] argues for analog computing by suggesting that there is "... a very decided psychological advantage in favor of the network analyzer since it bears such close resemblance to the actual power system ..." (p. 621). The author of [24] speculates that modeling choices are intertwined with computing capabilities, stating "... perhaps the knowns and unknowns commonly used for network analyzers have been influenced by that instrument's greater facility in handling data in one form ... 18 years of network analyzer experience may have influenced the engineer's thinking ..." (p. 622). Interviewee John Undrill recalled similar experiences of the relationship between computing technology and analysis method: "When you're sitting in front of an analog computer, it's just so logical, so natural to be thinking in terms of the Bode plot." (Undrill, 01:02:48)

By the mid-1950s, manufacturers offered digital computer models for computing *economy loading* (the terminology for what is now known as optimization) and power flow, but the limited memory and length of processing time to run equations curtailed adoption of these approaches [10]. In parallel, mathematicians experimented with sparse matrices, a method for reducing the total number of computation iterations needed to calculate the economic capacity of an industrial process [47]. Interviewee Noel Schulz explained electric utilities had been among the biggest users of mainframes, and for sparse matrix techniques, "the math was done by power engineers. Because they didn't have enough computational power to run all those scenarios." (Schulz, 00:08:19)

William Tinney, an engineer with the Bonneville Power Administration (see Figure 3), published a breakthrough solution in 1967 [78]. This mathematical innovation proved essential to power system engineers for advancing their power flow calculations. The sparse matrix method afforded engineers faster and more accurate computing on digital computers to better understand, optimize, and plan for their systems. As interviewee Anjan Bose offered, "everybody in the world who was working on this problem was using Newton-Raphson [*an algorithm for finding successively better approximations*], because everybody knew that Newton-Raphson was the best one to do. But we couldn't figure out how to run these huge, big matrices through.... The computers weren't big enough ... And he [*Tinney*] figured out a way on how not to have to multiply with zeroes a few million times, and which made it possible to then run it on this computer." (Bose, 00:50:45)

The ability to complete power flow calculations efficiently on digital computers contributed to the transition from analog to digital machines within the industry. Although digital machines for commercial applications had been available for nearly two decades, and many lauded the facility they provided for calculating economy loading, utilities still clung to their analog machines [12]. Following adoption of Tinney's sparse matrix method, interviewee Fernando Alvarado explained, "The one thing that disappeared instantly, instantly, was the hardware simulator. Within two years, once people were able to solve it—even with crude techniques—the more minimal power flow problem–the simulators–poof–disappeared. They weren't needed anymore." (part I. 00:35:57)

Tinney is widely recognized in power engineering

**TABLE 1.** Glossary of Key Technical Concepts.

| Sparsity | Stability | Optimization and Economic Dispatch | Time-Synchronized Measurements |
|---|---|---|---|
| Encoding the connection points and electrical characteristics of power lines and transformers, a specialized matrix, called an *admittance matrix*, relates the voltages and currents in an electrical network and is thus central to nearly all power system analyses. *Admittance* here refers to the ease with which current flows. Since most locations in a power grid are directly connected to only a few other locations, the admittance matrix is inherently *sparse*, that is, nearly all entries are zero (see Figure 2). Efficiently performing power system computations requires exploiting sparsity via linear algebra algorithms that avoid storing and calculating with the zero entries [76]. | As dynamical systems (those subject to a study of dynamics), power grids are modeled via differential equations that relate states of the system (frequency, voltages, etc.) and inputs (customer demands, target values, etc.) via a nonlinear function. The nonlinearity of these equations makes simulation and analysis difficult. The stability of the system can be inferred using a linear approximation that aims to accurately represent the nonlinear function around a nominal operating point [69]. Engineers classify power system stability issues into various categories depending on the mechanism by which an instability occurs [37]. | For economically efficient and reliable operations, engineers seek to dispatch the least costly generators while avoiding overloads of any power grid components. To compute a least-cost dispatch, operators solve constrained optimization problems that minimize the sum of cost functions dictated by the efficiency of each generator while satisfying equality constraints from a power flow model and inequality constraints from device capability limits (e.g., thermal limits on current flows through each line). Optimization problems are solved using algorithms from the field of operations research such as interior point and simplex methods [55]. | Operators rely on many measurements for situational awareness. Consolidating measurements across widespread geographic regions requires sensors to be time synchronized. With many disturbances occurring on time scales of several cycles of the 60 Hertz voltage and current waveforms, measurements must be consistently timestamped to millisecond precision. To achieve this, Phasor Measurement Units (PMUs) rely on time synchronization signals from Global Positioning Systems. PMUs enable many applications, such as stability assessments and root cause analyses (e.g., which failure has preceded another) [20]. |

for developing sparse matrix methods [29], yet the significance of this computational advance extends well beyond electrical systems. Researchers in applied mathematics and allied fields adopted and adapted Tinney's method during the ensuing years. Tinney's work is occasionally acknowledged outside the power field [23], [70].[3] As Alvarado offered, "My feeling is the real inventor [*of sparse matrices*] is the one, not only that had the idea, but applied it to a practical problem. And that's Bill Tinney." (Alvarado, Part I. 00:33:36) Bose suggested, "what people don't know is Bill Tinney is the one who figured out how sparse matrices could be exploited. And he became famous in the mathematics community. It is a bragging point for power engineers..." (Bose, 00:53:07) Interviewee Thomas Overbye was somewhat more sanguine, "Certainly, sparsity developed in different communities. Sparsity in the power domain, we would say we invented sparsity, but other communities would say they invented sparsity." (Overbye, 00:44:53)

Importantly, Tinney's 1967 publication [78] appeared hard on the heels of industry-wide concern about the 1965 Northeast Blackout. This first large-scale cascading power failure thrust the reliability of the electric power system into the public spotlight. Triggered by the unexpected tripping of a protective relay near Niagara Falls, the November 9, 1965 outage affected 30,000,000 customers in eight states and Ontario. Both within and beyond the industry, engineers, elected officials, regulators, and academics debated whether it was wise to continue building interconnected power systems [14]. According to the interviewees, utilities quickly turned to digital computing to address the future reliability of their growing networks. Bruce Wollenberg described beginning a job in 1966, and, shortly thereafter driving from Philadelphia to New York to discuss new computer systems with Consolidated Edison. He explained that the blackout "spurred on the whole technology of control centers doing contingency analysis and doing advanced SCADA [*supervisory control and data acquisition*]. The business went way up after that blackout." (Wollenberg, 00:46:56) He and his colleagues wanted to use Tinney's method for real-time power flows (Wollenberg, 00:22:28), which they later installed at several utilities including Consolidated Edison (Wollenberg, 00:23:30). As Bose explained, "in those days when power companies wrote software,

[3] In IEEE Xplore, Tinney's papers have well over 5,000 citations. Using search values of "sparse matrix," "sparsity," or "sparse matrices," however, only 49 of nearly 160,000 publications include Tinney's name. Search date: Oct. 30, 2025

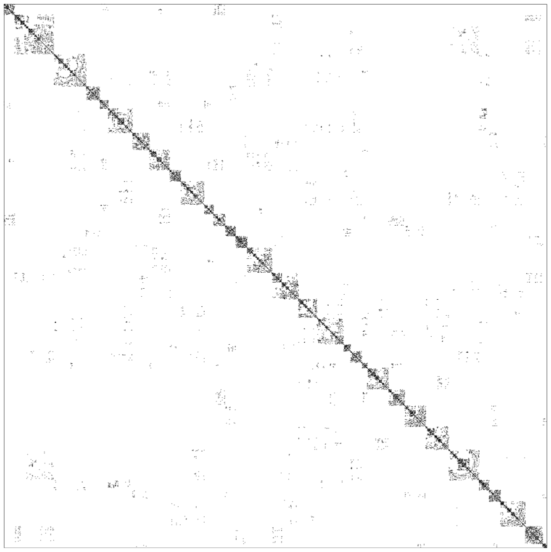

**FIGURE 2.** The admittance matrix for the 25,000-bus ACTIVSg25k test case representative of the US Northeast and Mid-Atlantic regions [6]. Each dot represents a non-zero value corresponding to a power line between the locations associated with the row and column. With 25,000 rows and 25,000 columns, 99.986% of the matrix entries are zero.

they gave it away." (Bose, 00:55:10)

For two decades, researchers in multiple disciplines considered approaches to using sparsity to speed up the cumbersome iterative calculation of large matrices. In 1967, engineer Bill Tinney, "sitting in a little cubicle in the bowels of the Bonneville Power Administration building in Portland figured it out." (Bose, 0054:13) This timely innovation provided power engineers with a critical tool for improving system reliability just as major cascading power failures became a reality for Americans. In addition, with this type of tool in place, utilities confidently installed digital computing systems in their planning and design departments and control rooms. The transition from analog to digital computing and control for utilities accelerated in the 1970s and was completed by the mid-1980s. In response to the practical demands of electrification, smart engineers developed and deployed algorithms that influenced both the direction of sparse matrix theory in multiple disciplines and the integration of digital computing into the power industry.

## Energy Crises, Voltage Collapses, and Computational Innovations That Mattered: 1970-1990

Expansion defined the nature of electrification in the United States across much of the mid-century. During the first three post-World-War II decades, 1945 to 1975, power demand increased close to 7% annually, and utilities used that figure to plan for system growth [15]. With larger generators, greater areas served by interconnected networks, more power moving across transmission lines, and customers relying on electricity for a multitude of activities, the operation of power systems grew increasingly complex. Across these years, power system engineers had looked to fast evolving computer hardware and software offerings for tools to address emerging challenges.

**FIGURE 3.** Tinney Photo: William Tinney with colleague at Bonneville Power Administration (BPA), date tbd, courtesy of BPA.

A series of disruptions across the broader energy economy influenced the direction of research and innovation in the next decades. Interviewee Nicholas Miller described the early 1970s as an "inflection point ... generation was getting bigger and the system was getting more stressed." (Miller, 00:12:34) By these years, in the context of notorious accidents and elevated environmental activism, Congress had passed and the president had signed legislation to curb air and water pollution. Judicial decisions followed, affecting the permitting of a wide array of industrial facilities including electric generating and pumped storage plants [2]. The 1973 and 1977 oil embargoes, imposed by the Organization of Arab Petroleum Exporting Countries

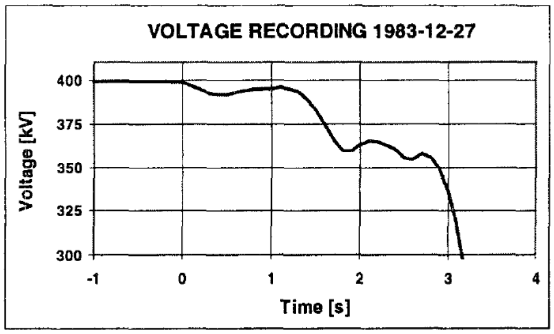


**FIGURE 4.** Measured voltage during the 1983 Swedish voltage collapse blackout as shown in [46]. As reported in [46], at $t$ = 3 seconds, the rate-of-change of the voltage was about 200 kV/s. *Permission to use required.*

(OAPEC), heightened public focus on energy industries [45], [85]. The 1977 New York Blackout further challenged utilities to demonstrate their ability to meet the power needs of their customers. As first President Richard Nixon and then President Jimmy Carter called for Americans to conserve energy, electricity customers reduced their energy use.

Until this moment utilities continued to propose and build new infrastructure with the intent of meeting an expected 7% growth in demand each year. The drop-off in energy use by the late 1970s only exacerbated other issues plaguing the industry. For decades, engineers had designed larger and more efficient generators, allowing utilities to keep the per kilowatt-hour cost of electricity down. But the generators met their thermal limits [38]. Inflation drove construction costs up. The Three Mile Island accident in 1978 and the Washington Public Power Supply System (WPPSS) bond default a few years later curbed public support for the increasingly expensive nuclear alternative to hydroelectric and hydrocarbon-fueled generation [62]. The 1980s brought additional technical challenges. Over the course of the decade, several unprecedented voltage collapses indicated that this was a gravely concerning phenomenon. Interviewee Göran Andersson, referring to a major 1983 blackout in Sweden (see Figure 4 from [46]), explained, "that was something that was not studied that extensively up to that date. And there were other places in the world that had experienced voltage instabilities. So that was a very hot topic." (Andersson, 00:07:27) While the proximate causes varied, significant voltage collapses also occurred in Quebec, Belgium, France, Japan, and the United States.

In short, the power industry faced a decline in demand and a loss of public support just as investment in growth was at an all-time high, amid a series of noteworthy stability and reliability events on power grids around the world. The search was on for new methods for assessing grid stability. This played out in engineering labs as well as system operating rooms across the country, as described by several interviewees. Andersson underscored a mismatch between model simulations showing a stable system in Sweden and the voltage collapse that resulted in the blackout in 1983. Fernando Alvarado explained that the interest in his most cited paper, published in 1993 and offering a calculation to determine the point beyond which additional power flow would lead to collapse, followed the heightened concern of the 1980s [11]. (Alvarado, Part I, 00:56:46) David Hill reflected, "the computation was such that it was a serious endeavor to look for these direct methods [*an approach for calculating transient stability*] in order to analyze all the contingencies on the grid. Using simulation had its limitations. It couldn't be done fast enough." (Hill, 00:21:50) Daniel Kirschen echoed, "getting things to go faster was always a concern." Miller explained that even if one built a good model, it could take a week to run the program and use up all the available disc space at a company as large as his employer, General Electric. As Hill noted, "systems were collapsing, and people didn't understand why, and they didn't know how to prevent it." (Hill, 00:21:50)

For power systems engineers, bigger and faster computers alone proved insufficient to address the mysteries of instabilities. For decades, engineers had assumed that a set of well-known computations, known as *direct methods*, would reveal causes and aid in designing systems to avoid this problem. These computations attempted to calculate whether the system would remain stable after a particular set of disturbances occurred. No matter the size or speed of the computing machine, however, limitations in the theory underlying direct methods challenged their ability to analyze stability characteristics for systems relevant to practicing engineers. As power systems engineer Lester H. Fink put it in 1980, "In my view, one of the hindrances to the advancement of our capabilities for dealing with evolving power system problems has been the continuing availability of bigger and faster computers: the continuing temptation (fortunately not always succumbed to) has been to solve newer problems by crunching more numbers, and it is only recently that more powerful alternative approaches are being considered and exploited" [31]. In this opening to a conference bringing together mathematicians and power system engineers, he called for the primacy of defining the problem and openness to emergent analytical techniques.

Indeed, specialists from outside power engineering brought new insights to the problem of voltage collapse. Hill, for example, expressed a lifelong interest "in the whole idea of systems" (Hill, 00:01:11) and pursued theoretical research on stability and systems control. He attributed his opportunity to apply this work to power systems to US federal funding in response to the energy crises of the 1970s. His work focused initially on revising the model used with direct methods. Later, he applied this approach to find "a simple model that captured the behavior" of a dynamic system to explain the 1983 voltage collapse in Sweden. (Hill, 00:09:24) Andersson underscored that he trained in mathematical physics, and was lured into power systems to work on control and computational techniques. With his graduate students, he developed methods for calculating how much load could be added to a system without leading to voltage collapse, using a *minimum singular value* method.[4] Andersson noted that they had difficulty "selling the concept to other engineers" because it was "an exotic animal to most of them." (Andersson, 00:10:03) Yet, the power system community adopted his approach in the wake of the 1983 voltage collapse in Sweden.

Despite the advances in computing machinery and software technologies during the 1970s and 1980s, some of the thorniest problems for power systems engineers called for new theoretical approaches. The methods that had proved sufficient for planning and analysis in earlier years failed to provide insight into the voltage collapses experienced in the 1980s. As interviewee Christopher DeMarco offered, "Frankly, what had been left out, historically, in models was well recognized. It was just a long period of time where people convinced themselves, 'what we're leaving out is not relevant to the phenomena we care about.'" (DeMarco, 00:21:24) Without new theoretical underpinnings, better assumptions, and models that addressed dynamic conditions on the grid, the power and speed of supercomputers did not provide the advances needed. However, by the end of the decade, again quoting Hill, "the computation caught up," meaning that the advances in modeling and theory enabled engineers to exploit the latest computational machinery. As interviewee Thomas Reddoch explained it, the visionaries of this era took known analytics from other fields of study, demonstrated how they could be applied to power systems, and then "the tools of implementation would come along." (Reddoch, 00:45:16)

## Restructuring and Recalculating an Evolving Power System: 1990-2010

The Public Utility Regulatory Policy Act (PURPA), passed by Congress in late 1978, ushered new actors into the power generation field. The act required monopoly utilities to buy power from co-generators and from alternative generating sources using novel technologies. While these participants provided only a minuscule percentage of the total electricity produced in the United States at that time, they demonstrated that the long-time industry structure of vertical monopoly utilities regulated by state commissions was not the only, nor necessarily the best, approach to electrification.

By the early 1990s, within a wave of deregulation across other industries and in other countries, Congress and several state legislatures rewrote their laws to allow competition among power generators and to require open access to transmission lines. In many regions of the country, utilities disaggregated their component parts. Some continued to own and operate transmission or distribution systems as regulated monopolies. Others entered competitive wholesale power markets through newly independent generating companies. The Federal Energy Regulatory Commission (FERC) also ordered the establishment of Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) to physically operate grids and manage the new markets. By the early 2000s, the power industry looked quite different from its historical configuration.

During these years, developers bet on utility-scale wind and, later, solar power. Many states established hard targets—generally called Renewable Portfolio Standards—for the percentage of wind and solar in their energy mix. Federal and state tax incentives further favored these resources. As a result, not only had the regulatory regime and industry configuration restructured, but the technologies used to power the grid had begun a new cycle of evolution, calling for novel technical methods to keep the lights on.

Adoption of computing exploded across the US economy during these same years. In 1984, 8% of US households reported owning a computer. By 2015, that number grew to 79% [68]. Among myriad advances in computer hardware and software, interviewees pinpointed several milestones that made a

[4]The minimum singular value is a quantity that indicates how small disturbances in the power demanded or generated impact the voltages. This quantity approaching zero indicates that the system is nearly unstable.

difference to their work. The advent of microprocessors, supercomputers, desktop workstations, personal computers, and, eventually, laptop computers offered power, speed, and the ability to run programs at a distance from a computing center. Access to these machines facilitated modeling, simulation, and data processing. New languages and libraries, including UNIX, MATLAB, SPARC, and CPLEX, supported programming tailored to power system needs. Several interviewees seized on innovations to address unsolved power system challenges and, in some instances, to build entirely new businesses.

According to Bruce Wollenberg, for example, MATLAB was “God’s gift to electrical engineers.” (Bose-Wollenberg Interview 01:25:58) According to historian Thomas Haigh, electrical engineers adopted MATLAB early on for control theory and signal processing [36]. Originally built around computing matrices, MATLAB introduced sparse matrices in 1992 [50], making it especially valuable for engineers like Wollenberg who had laboriously written power flow algorithms in FORTRAN for use on mainframe computers. MATLAB worked on multiple types of computing machines, including small and portable personal computers [36]. Wollenberg described going from FORTRAN to MATLAB as “up on the ceiling!” (Bose-Wollenberg 01:25:58) As Fernando Alvarado noted, by 2000, it was no longer necessary to teach a course on sparse matrices because MATLAB could do everything except specialized applications. (Alvarado, Part II, 00:07:17) What had once been a tedious computational process for power system engineers had become a much more usable software tool, leading to more rapid prototyping of algorithmic improvements.

The industry restructuring of the 1990s introduced new actors to electric power systems, many of whom had no engineering background. As interviewee Thomas Overbye put it, “a lot of people ... were wondering: ‘How does the grid operate? What do these transmission lines do? ... What is loop flow all about?’ ” (Overbye, 00:08:07) To this date, system operators had versions of graphical displays in utility control rooms, but students, investors, lawyers, and regulators grappling with the complexity of power grids had neither intuitive understanding of the networks nor visualizations to facilitate comprehension. Overbye addressed this challenge early in his career, latching onto new capabilities of personal computers (PCs). He noted that there was other software available that could analyze power systems well, but none married that capability to visualizations. With funding from the Edison Electric Institute in 1993, Overbye and colleagues at the University of Illinois at Urbana-Champaign worked on simulations that included animated displays to teach power system concepts to “non-technicals.” (Overbye, 00:13:03) The team commercialized the resulting product, PowerWorld, in 1996. PowerWorld provided improved legibility of the grid to industry engineers and outsiders alike, exploiting both the increasing flexibility and computing power PCs attained through the 1990s and into the 21st century (see Figure 5 from [59]).

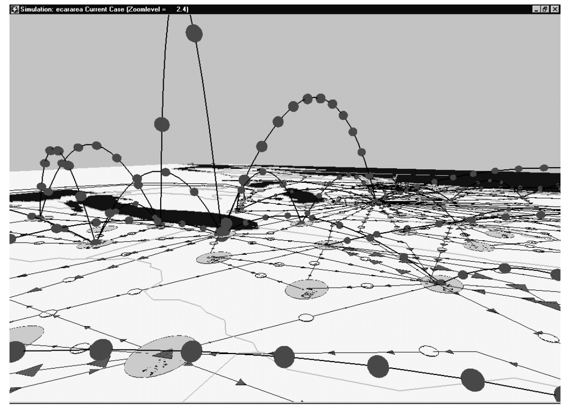

**FIGURE 5.** Interface for PowerWorld from [59] showing a comparison of different models for power flows from Wisconsin to the Tennessee Valley Authority. *Permission to use required.*

As power system analysis became increasingly complex in these years, processing on mainframes and minicomputers failed to be efficient. Interviewee Bahman Hoveida recalled that the lack of adequate computing resources to solve large power system problems was the biggest technical challenge he embraced when he joined the industry in the 1980s. He was motivated to address this problem when he recognized the processing ability and memory handling offered by microprocessors. In 1992, he and his colleagues started Open Systems International (OSI), a software company targeting the power industry. His team developed “applications for monitoring and control of the power system, including distribution and generation.” (Hoveida, 00:03:22) By writing a power flow application, among other solutions, that could run faster on a 486-chip computer than on a mainframe, Hoveida offered a more cost-effective approach to system analysis. While PowerWorld made power systems more legible to newcomers to the industry, OSI offered less expensive and faster solutions to ongoing computation challenges posed by the grid. Both took advantage of the smaller, faster, less expensive, and more powerful computing machines that arrived on the market just as new players joined the power industry.

Competitive wholesale power markets created challenges for system operators. For the markets to function, generators had to plan how much electricity they would make available at a price that would cover their costs, allow them to compete successfully, and produce a profit. At the same time, operators had to plan ahead to determine when to start up and shut down generators and then adjust the generators' outputs in real time to meet demand at every moment. These processes are called *unit commitment* [60] and *optimal power flow* [3], [52]. Markets began to operate, and still do, across multiple timescales while operators respond to continuous changes. System operators use various computational approaches to optimize grid performance both in terms of cost and reliability.

Alongside making schedules for sports leagues, unit commitment problems are among the most challenging optimization tasks, involving multiple discrete decisions on when to start up or shut down generators [7]. Through the 1980s and 1990s, industry participants used an approach called Lagrangian relaxation to address optimization, which often resulted in an infeasible solution. Interviewee Richard O'Neill described his familiarity with an alternative, called mixed integer programming, of which the utility industry was skeptical. The Electric Power Research Institute, for example, in 1989 indicated that mixed integer programming was a powerful modeling tool but was "theoretically complicated and computationally cumbersome" [35, p. 2.2], i.e., it would not work in practice [8].

As Director of the Office of Economic Policy in the Federal Energy Regulatory Commission (FERC), O'Neill organized the Next Generation of Unit Commitment conference in 1999, at which software developers and utilities discussed the computation conundrums. For example, efforts to solve a challenging week-ahead unit commitment problem, according to O'Neill, were unsuccessful due to insufficient computer capabilities. Robert Bixby, an inventor of the mixed integer optimization solver CPLEX, learned of this week-ahead unit commitment problem at O'Neill's conference. He then loaded the data onto his personal computer and used CPLEX to solve this problem within 22 minutes. In contrast, conventional Lagrangian relaxation approaches made no progress on a simpler two-day problem variant after eight hours of mainframe computing time. Recalling the presentation he gave on this result the next day, Bixby remarked that the audience was "blown away ... they realized ... we can really use mixed integer programming." [8, (36:52)].[5] Figure 6 from [7] shows the speed improvements achieved by CPLEX from 1991 to 2008 on mixed integer problems.

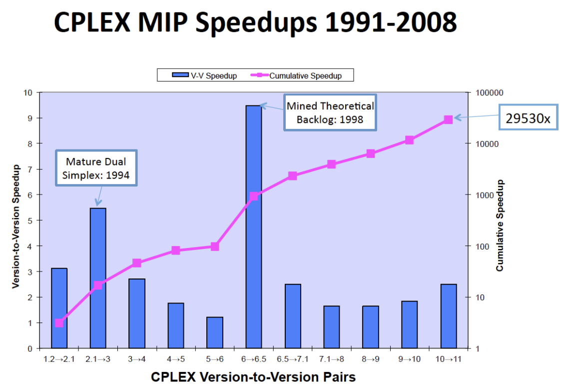


**FIGURE 6.** Computational speed improvements across versions of the mixed integer programming optimizer CPLEX from 1991 to 2008 as reported in [7]. In aggregate, CPLEX in 2008 was 29530 times faster than in 1991 for mixed integer problems. Key innovations for particular version upgrades are labeled on the figure. *Permission to use required.*

O'Neill noted that industry waited six years to adopt the mixed integer solution. In his recollection, the Pennsylvania-New Jersey-Maryland Interconnection (PJM) finally ran the program in 2006 and saved $500,000,000 in dispatch costs. When asked why the ISOs were reluctant to adopt this new approach, O'Neill speculated that the software they used had no modularity, and hence it would have been difficult and costly to change out one programming function while leaving the others in place. He explained, "there is a significant inertia in the industry. ... First [*it*] is very cautious, and secondly, anything you do on the system essentially creates a risk of creating a problem." (O'Neill, 00:42:10) While engineers tested their algorithms directly on power systems earlier in the century, by this date, they were reluctant to experiment on the operating grid without first running extensive computer simulations, lest they cause a blackout.

At this same time, the North American Electric Reliability Corporation (NERC) and its member entities wrestled with a different result of competitive power markets. Because electricity physically flows across the wires proportionally to their impedances, power does not necessarily follow the same path as financial transactions. Hence, regardless of who is buying power from whom on the wholesale market, the electricity will abide by the rules of physics as it moves from generators to customers, and may cause problems as a result. Interviewee Robert Cummings, then an engineer with NERC, developed the Interchange Distri-

[5]In 2017, the mixed integer optimization solver Gurobi solved this particular week-long unit commitment problem in 17 seconds [8, (40:43)].

bution Calculator, an algorithm for tagging and tracking power flows. He described traveling across the country to demonstrate the calculator to grid operators, and meeting with reluctance to adopt this approach. In one instance, he recalled that operators from New York said "'well, we don't have any computer that can do that.' And I closed my computer and I handed it to 'em. I said, 'here, now you do.' You had to sort of hit some people over there with a stick in order to get them to understand that this is the way it was going to work, and not doing it that way was not going to work." With personal computers and laptops, the excuses of costly mainframes and slow computing time were no longer credible.

Both longstanding computational challenges and new problems resulting from industry restructuring became tractable as engineers turned to the emerging computing technologies of the 1990s. By the turn of the century, system planners, transmission operators, academics, regulators, and engineering entrepreneurs adopted first personal computers and then laptops to implement their new algorithms and offer new software and simulation products. In several interviews, the team asked the engineers if it would have been possible to resolve challenges such as optimization with just computing improvements or just methodological improvements. Hoveida echoed the other interviewees when he said, "No, I think definitely the combination really helped accelerate the transition ... there [*were*] a lot of clever tips and tricks in formulating an optimization problem that would help reduce your search space. All of that was algorithmic. And then on top of that, you had the better computers." (Hoveida, 01:05:09)

## Synchronizing Time: 1916-2010

While profit and service are the two major motivations for building power systems, outages are the bane of the industry. Following plant failures, line faults, voltage collapses, and cascading failures, engineers, operators, and regulators engage in event analysis to discover what triggered the problem, how it proceeded, and what could have been done to prevent it. Historically, they began with interviews of system operators and then proceeded to collect available data to assess what had happened, where, when, and why. In 1916, famed engineer Charles Steinmetz had already inscribed the importance of accurate recording of operations, including the time, "so that the sequence of events recorded can be checked within a fraction of a second." [74, p. 399].

In 2003, following the second and larger major Northeast Blackout, investigators accessed a variety of data sources to reconstruct the events and eventually identify the origins of the outage and the sequence of cascading failures that followed [80, p. 181]. By this date, the industry adhered to a planning standard requiring the use of recording devices for disturbance monitoring. One detail, however, could have improved the analysis process: synchronized time across the system [80, p. 162]. "On August 14, [*2003*] time recorders were frequently used but not synchronized to a time standard." The final event report noted that "at a relatively modest cost, all digital fault recorders, digital event recorders, and power system disturbance recorders can and should be time-stamped at the point of observation using a Global Positioning System (GPS) synchronizing signal." Indeed, the advent of satellite-based atomic time-keeping aligned with a long history of intertwined clocks and power grids.

From the 1800s onward, tinkerers and inventors experimented with electric clocks to replace pendulum clocks [14]. In 1918, Henry Warren patented a clock that relied on connection to a power network operating at 60 Hz to provide reliable and consistent time. This proved a boon to power companies in two ways. First, operators used this clock to help maintain steady frequency on the network. By comparing the electric clock's hands to the hands on a high-precision pendulum clock set to Naval time they could see in an instant if the frequency was too high or too low. This was especially valuable when interconnecting with other networks. Second, by selling clocks that operated only when connected to the central power station, a company assured a small but steady source of demand for electricity, which helped with operating efficiency.

Over the decades, slight differences in time-keeping between interconnected systems proved problematic. For example, in 1962 when utilities were considering links to connect the Eastern and Western Interconnections, they worried that it could take an hour for a time error to propagate from one coast to the other [44]. The utilities addressed time-error to improve frequency control in their voluntary standards beginning in the 1960s. Indeed, Bahman Hoveida noted that one of the reasons utilities were reluctant to switch from mainframes to OSI's virtual operating systems in the early 1990s was "some of these microprocessors did not have the right clocking ... I think that was the argument that, since you need such precise time ... for time synchronization ... some of these microprocessors did not at the time possess this precise clock. You could always have satellite clocks that provide input into your process, but anyhow, that was the argument." (Hoveida, 00:20:14)

Parallel developments in satellite technology and data-relaying systems on grids mitigated these challenges. Satellite-based time-keeping offered a new approach to synchronizing multiple devices on the ground. In 1964, the US Navy launched the Timation satellite program, intended to broadcast an accurate time reference. The Timation satellites foregrounded the development of the Global Positioning System (GPS), initiated by the Department of Defense in 1973. The full suite of 24 GPS satellites was operational by 1993, and initially available for limited civilian use, becoming fully available in the early 2000s. Access to synchronized time without additional calculation promised new forms of functionality for power system engineers.

In 1983, Arun Phadke, James Thorp, and Mark Adamiak at Virginia Tech proposed using a microcomputer to directly measure voltage phasors and provide real-time data about system conditions to operators [61]. They suggested that this information would simplify algorithms, provide timely analysis, and lead to control procedures that would further stabilize the grid. Phadke acknowledged that synchronization of a measurement system over a wide geography was crucial to its efficacy, and noted the potential of using GPS synchronization, but averred that it would be costly to implement [**?**]. Phadke and Thorp introduced the Phasor Measurement Unit (PMU) in 1988 and Macrodyne offered a commercial model in 1992. By the mid-1990s, utilities experimented with the placement of PMUs that locked their internal clocks to the GPS reference clock [84]. The 1995 IEEE standard for PMUs identified the US GPS as well-suited for synchronized phasor measurement systems [42]. Experimentation with PMU installation continued through the 1990s, and, perhaps unsurprisingly, met with widespread industry adoption following the 2003 Northeast Blackout.

The advent of PMUs with GPS time proved significant. Göran Andersson affirmed that, with GPS, digital computer models provide good recordings when something goes wrong, “GPS, they are timestamped, so you know exactly when they’re happening. So, at different places in the network, you can see what happens, and you [*can*] time-synchronize it. That is something that is really good.” (Andersson, 00:47:17) But until the cost came down, power system engineers looked for less expensive ways to spot and analyze outage causes. In the mid-1990s, the Electric Power Research Institute (EPRI) had identified voltage sags on transmission lines following a fault as a problem for power quality. Utilities were interested in identifying and rectifying voltage sags, but not with the $8000 monitors required to detect them. Interviewee Deepak Divan described development of a monitoring system that pulled in data from many locations at a very low cost. He explained, “We took the Motorola phone, DSP—which was over five bucks—and we built the power monitors system ... ” His team offered the monitors to utilities for free, and, after installing 140, “the data started pouring in.” (Divan, 00:31:00) At the time of the 2003 Northeast Blackout, they had about 250 monitors installed in the region and were able to begin publishing the location of voltage sags within hours of the initial fault.

In a similar vein, interviewee Yilu Liu described developing a “poor man’s PMU” while waiting for the cost of Phadke’s PMUs to come down. Her team wanted to create a platform that would enable students to observe and study real grid phenomena. In the early 2000s, a collection of undergraduate students, signal processing faculty, and power systems engineers collaborated to develop a device that linked frequency measurements taken at a standard electrical outlet with GPS signals to synchronize samples. According to Liu, companies like ABB and the Tennessee Valley Authority liked the portability of the design and sponsored the work. Using a network of “friends and family,” Liu’s team deployed these devices to thousands of locations around the world. Academic, government, and industry researchers rely on Liu’s network, FNET/GridEye, for monitoring and analyzing a variety of conditions on grids. Liu explained that the power industry benefited from the adoption of GPS in other industries, especially transportation, which brought the cost down and made it feasible for her to use this technology.

Interviewee Robert Dent reflected on the value of synchronized time data. Without it, sequence-of-event recorders were informative, but not definitive. “Whenever you see an event that happens, you always kind of wonder, ’gee, that capacitor bank tripped out and the transformer tripped out, but which went first?’ ... the sequence-of-events recorder says this happened at this time. And at the other location ... it tells you the time, but can you really trust it that much because somebody is setting that time in each location.” (Dent, 00:27:16) Once satellites incorporated synchronized time signals, and the information became available for civilian use, power system engineers seized on the opportunity to address the decades-long problem of analyzing outages. With the capabilities of microprocessors, Phadke and his colleagues built PMUs and later incorporated GPS time, providing a now indispensable tool for approximating real-time simulation of grid operations and post-event analysis. Others developed less costly devices to measure voltage and frequency conditions, integrating synchronized time to make them valuable tools for education, research, operations, and event analysis.

## Conclusion

Although retirement beckons for many of the participants in the oral history project, most are still actively involved in the grid transition underway today. The well-documented changes to the power grid–from integration of inverter-based resources, to electrification across multiple economic sectors, increasingly distributed generation, generation behind the meter, and projected dramatic increases in demand driven by development of new data centers–pose challenges to power systems engineers. Grid stability, reliability, and resilience are at stake, as is operating efficiently and equitably to assure customers have access to power when they need it at an affordable price. Indubitably, computational tools will be part of the solutions.

Interviews offered both caution and optimism when glancing ahead. Bahman Hoveida echoed several other interviewees when he said, “The power grid is becoming more complex, not only in terms of size, it’s getting bigger, but also integrating renewables, batteries, what have you. It’s expanding the size of the problem that needs to be solved.” (Hoveida, 01:13:28) Yilu Liu regarded this future as job security, “becuase this grid is going to be much harder to deal with." (Liu, 00:27:33) Zeroing in on a renewables-rich grid, Alexander Papalexopoulos offered, “we’re moving to a weather-sensitive system, we need a new design, and we need new models and new software.” (Papalexopoulos, 00:16:43) He noted that emerging Artificial Intelligence (AI) tools are “expected to solve many problems, forecasting problems, prediction problems, [*and*] do better diagnostics, improve maintenance, improve reliability.” (Papalexopoulos, 01:07:09) But he acknowledged a negative side, “Data centers will prove to be one of the most intensive energy loads that we have.”

> *“Right now, you’re hearing people talking about data science and AI and all this good stuff. The same thing will happen. These are people who haven’t experienced this <laugh> because the AI technology will far surpass the ability to come up with clever algorithmic changes that you can in research. So, keep that in mind.”—Anjan Bose, Oral History Interview, January 23, 2024*

Once again, the nature of the power grid’s expansion continues the recursive cycle. As Anjan Bose reflected in the quote above, by the time engineers resolve the computer application, the computer changes. Thomas Reddoch seemed to agree, “... our systems are becoming more and more complex, and analytical tools will sit at the root of us being able to move forward (Reddoch, 01:17:11) ... You can rest assured that AI is not the last stop—it’s just the current stop.” (Reddoch, 01:21:47)

Through interviews with experts who tackled the growing pains of grid expansion, several aspects of the intertwined histories of power grids and computing emerged. In some instances, the computers were too slow and had insufficient memory to solve complex calculations. In others the underlying algorithms rendered the process lengthy and difficult. New computational approaches, new methodologies, and new approaches to modeling and simulation met improvements in computing machinery and software just in time. Interviewees remarked on the valuable exchanges between power system engineers and experts in adjacent disciplines that took place throughout these experiences. In yet other instances, power engineers noticed the functionality offered by emerging computer hardware and software and exploited this to address longstanding problems that had been ignored or were computationally intractable. Engineers adapted commercial software and developed new software to accelerate power flow and optimization computations, and brought forward visualization and power tracing to address the pragmatic challenges of industry transition. They integrated apparatus from other fields to make grid behavior more legible. The adoption of these solutions brought modernized and affordable measuring, recording, modeling, computing, and analyzing devices into power system research labs, planning centers, and control rooms. The engineers did what engineers in both computing and electrification have always done – compared, competed, collaborated, and cobbled together solutions to address the ever-evolving complexity of their respective systems and the infrastructures that rely on them.

## Appendix: Oral History Interviewees

Table 2 lists the 41 interviewees who participated in oral histories along with the interview details.

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**TABLE 2.** Oral History Interviewees

| Name | Title | Employer | Date | Lead Interviewer | Location |
|---|---|---|---|---|---|
| Fernando Alvarado | Professor Emeritus | University of Wisconsin–Madison | October 16, 2024<br>November 20, 2024 | Julie Cohn | Online |
| Gören Andersson | Professor Emeritus | ETH Zürich | October 24, 2023 | Julie Cohn | Online |
| Ross Baldick | Professor Emeritus | University of Texas at Austin | November 21, 2024 | Julie Cohn | Online |
| Jessica Bian | Vice President of Grid Services | Grid-X Partners | July 24, 2024 | Julie Cohn | Seattle Convention Center, Washington |
| Janusz Bialek | Professor | Newcastle University | July 17, 2023 | Julie Cohn | Hyatt Regency Orlando, Florida |
| Anjan Bose | Regents Professor | Washington State University | July 18, 2023 | Julie Cohn | Hyatt Regency Orlando, Florida |
| Anjan Bose & Bruce Wollenberg | Regents Professor & Professor Emeritus | Washington State University & University of Minnesota | May 26, 2025 | Julie Cohn | University of Minnesota, Minneapolis, Minnesota |
| Mukul Chandorkar | Professor | Indian Institute of Technology – Bombay | July 15, 2023 | Julie Cohn | Marriott Hotel, Orlando, Florida |
| Hsiao-Dong Chiang | Professor | Cornell University | July 17, 2023 | Julie Cohn | Hyatt Regency Orlando, Florida |
| Joe Chow | Institute Professor | Rensselaer Polytechnic Institute | July 17, 2023 | Julie Cohn | Hyatt Regency Orlando, Florida |
| Robert Cummings | President | Red Yucca Power Consulting | January 17, 2024 | Julie Cohn | Online |
| Christopher DeMarco | Professor Emeritus | University of Wisconsin–Madison | July 25, 2025 | Julie Cohn | University of Wisconsin–Madison, Wisconsin |
| Robert Dent | Retired | New York Power Authority | July 23, 2024 | Julie Cohn | Seattle Convention Center, Washington |
| Deepak Divan | Professor Emeritus | Georgia Institute of Technology | January 25, 2023 | Julie Cohn | Georgia Technical Institute, Atlanta, Georgia |
| Nikos Hatziargyriou | Professor Emeritus | National Technical University of Athens | July 18, 2023 | Julie Cohn | Hyatt Regency Orlando, Florida |
| David Hill | Professor | Monash University | January 23, 2024 | Julie Cohn | Online |
| Ian Hiskens | Vennema Professor of Engineering | University of Michigan | July 19, 2023 | Mahbubul Bhuiyan | Hyatt Regency Orlando, Florida |
| Bahman Hoveida | Founder & Former President/CEO | Open Systems International | October 29, 2024 | Julie Cohn | Online |
| Mladen Kezunovic | Regents Professor | Texas A&M University | June 10, 2025 | Julie Cohn | Texas A&M University, College Station, Texas |
| Harold Kirkham | Staff Scientist | Pacific Northwest National Laboratory | July 24, 2025 | Julie Cohn | Seattle Convention Center, Washington |
| Daniel Kirschen | Donald W. and Ruth Mary Close Professor | University of Washington | July 22, 2025 | Julie Cohn | Seattle Convention Center, Washington |
| James Kirtley | Professor | Massachusetts Institute of Technology | July 18, 2023 | Sutanwi Chatterjee | Hyatt Regency Orlando, Florida |
| Mark Lauby | Senior Vice President and Chief Engineer | North American Electric Reliability Corporation | July 18, 2023 | Mahbubul Bhuiyan | Hyatt Regency Orlando, Florida |
| Bernard Lesieutre | Professor | University of Wisconsin–Madison | July 25, 2025 | Julie Cohn | University of Wisconsin–Madison, Wisconsin |
| Yilu Liu | Governor's Chair Professor | University of Tennessee | July 19, 2023 | Sutanwi Chatterjee | Hyatt Regency Orlando, Florida |
| Jean Mahserdjian | Professor | Polytechnique Montreal | July 19, 2023 | Julie Cohn | Hyatt Regency Orlando, Florida |
| John McDonald | Director (Retired) | GE Grid Solutions | January 25, 2023 | Julie Cohn | Georgia Technical Institute, Atlanta, Georgia |
| Sakis Meliopoulos | Georgia Power Distinguished Professor | Georgia Institute of Technology | July 22, 2024 | Julie Cohn | Seattle Convention Center, Washington |
| Nick Miller | Principal | HickoryLedge LLC | July 23, 2025 | Julie Cohn | Seattle Convention Center, Washington |
| David Nevius | Senior Vice President | North American Electric Reliability Corporation | January 12, 2024 | Julie Cohn | Online |
| Richard O'Neill | Distinguished Senior Fellow (Retired) | US Department of Energy ARPA-E | October 25, 2025 | Julie Cohn | Online |
| Thomas Overbye | Professor | Texas A&M University | June 10, 2025 | Julie Cohn | Texas A&M University, College Station, Texas |
| Patrick Panciatici | Scientific Advisor | RTE France | July 19, 2023 | Julie Cohn | Hyatt Regency Orlando, Florida |
| Alex Papalexopoulos | President, CEO & Founder | ECCO International | July 23, 2025 | Jessica Slater | Seattle Convention Center, Washington |
| Robin Podmore | President & CEO | Incremental Systems Corporation | July 23, 2025 | Julie Cohn | Seattle Convention Center, Washington |
| Thomas Reddoch | Senior Technical Executive | Electric Power Research Institute | May 28, 2024 | Julie Cohn | Online |
| Bob Reedy | Consultant | Lindahl Reed Inc. | July 23, 2024 | Julie Cohn | Seattle Convention Center, Washington |
| Noel Schulz | Bob Ferguson Endowed Professor | Washington State University | July 22, 2024 | Julie Cohn | Seattle Convention Center, Washington |
| John Undrill | Principal Consultant | GE Energy | July 16, 2025 | Julie Cohn | Online |
| Vijay Vittal | Regents Professor | Arizona State University | July 14, 2023 | Julie Cohn | Marriott Hotel, Orlando, Florida |
| Bruce Wollenberg | Professor Emeritus | University of Minnesota | May 26, 2025 | Julie Cohn | University of Minnesota, Minneapolis, Minnesota |