Survey of High Impact Electric Power System Papers, 1975-2024

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***Abstract*—**This paper discusses results of an informal survey intended to identify the most impactful electric power system papers from 1975 to 2024 written in English. The survey was shared primarily over email to a large number of electric power engineers asking them to identify up to three papers that they consider among the most impactful papers of the last 50 years. A total of 144 valid responses were received, identifying 101 unique publications. Of those publications, 18 received multiple votes. The paper receiving the most votes are in the areas of electricity markets, optimal power flow, synthetic electric grids, voltage phasor measurements, electric grid stability, and associated with the open-source power system analysis program. This paper is a follow-up to a 2000 paper identifying the top papers of the 20th century.

Index Terms—*electric power systems, high impact papers, power engineering literature, 50 years*

I. Introduction

After more than 160 years of commercial use, electricity has transformed human society. As noted in [1], the majority of the top 20 engineering achievements of the 20th century would not have been possible without electricity. As a result, the top ranked achievement in [1] is the development of large-scale interconnected electric grids that made electricity ubiquitously available to many. This widespread electrification required the collective efforts of millions, and the ingenuity and hard work of thousands of engineers in many different disciplines. Certainly crucial to this is electric power systems engineering, which is focused on the design and operation of the large-scale electric grids that supply most of the world's electricity. While electric power systems engineering was important in the 20th century, it's importance has only accelerated in the 21st century, as the electric grid supports continued electrification and sustainability efforts around the world. As we finish the first quarter of the 21st century, the focus of this paper is to highlight some of the research work that forms the foundation of these ongoing engineering achievements.

There are several ways in which advancements in engineering practice are disseminated including through presentations, journal and conference articles, books, magazine articles, reports, patents, industry standards, software and more recently webinars. While some of these are private, such as the exchange of trade secrets within a single organization, much is public. This public dissemination of knowledge helps to advance the field, and certainly one of the most impactful and lasting means of documenting and communicating progress is through technical journal and conference papers. To facilitate the further propagation of knowledge, we believe it is useful to identify the most impactful of these papers. This was done in 2000 using a survey approach [2] looking at determining the highest impact publications in power engineering from the 20th century (1900 to 1999). The purpose of this paper is to update and extend this prior work to include the first quarter of the 21st century.

In the original paper [2] a total of 39 publications were identified, including journal and conference articles, books and reports. Of the top eight all but one were journal or conference articles, and all were written before 1975. The top paper in [2] is "Method of Symmetrical Co-Ordinates Applied to the Solution of Polyphase Networks" from 1918 by Fortecue [3]. The second paper is "Two Reaction Theory of Synchronous Machines" from 1929 by Park [4] presenting what would become known as Park's Transformation, while the third is "Digital Computer Solutions of Power Flow Problems" by Ward and Hale from 1956 [5]. The latest publication in the top eight is "Fast Decoupled Load Flow" by Stott and Alsac from 1974 [6]. All of the publications in [2] were written in English. Note that the terms "power flow" and "load flow" have been used synonymously since at least the 1950's.

Since none of the top papers in [2] were written after 1974, we decided to ask the power system community to identify the most important papers from 1975 to 2024, or the last 50 years. We employed a survey process that largely mirrors the one used in [2]. That is, we issued a wide and open call to our colleagues in the electric power system community, asking them to identify the journal or conference publications that they view as the most impactful of the last 50 years. Recognizing the difficulties in trying to identify publications in different languages, the focus was limited to publications written in English.

One primary means for disseminating this request was the use of Power Globe, an Internet remailer facility with about 7500 members that has been used for more than 30 years to broadcast information on electric power engineering worldwide [7]. Several other email lists were also used, along with informal communication to a variety of colleagues. The specific request was for people to identify up to three of the highest impact papers written in the last 50 years (1975-2024) and to indicate why they thought the papers are important. People were not allowed to nominate papers in which they were a co-author. A Google Form was provided for the responses, though people could also email their selections. For identification they needed to provide their name, email and affiliation. The responses were collected between late August and early October 2024.

II. Status of Electric Power Engineering in 1975

Before presenting the results, it is useful to first summarize the state-of-the-art in electric power systems engineering at the beginning of our 50 year survey period. Physically speaking, the electric grid of the late 1970's was similar to the grid of today, at least in the developed world. Large electric grids interconnected continents with transmission levels of up to 765 kV in North America, with most electricity supplied from large generating stations. Thanks to rural electrification efforts decades earlier, almost everyone had access to grid-supplied electricity. The late 1970's was the era of the vertically integrated utilities. Tie-line bias control allowed utilities to fairly easily interchange power, with [8] providing a good history on the development of this technology. While there were fewer environmental regulations than today, the first Earth Day in 1970 was instrumental in the creation of many new requirements in the planning and operation of the electric grid. The 1973 oil crisis helped to dampen the previously high electricity growth rates, and electricity prices started to increase.

From an engineering perspective 1975 was in the middle of the rapid computerization of power system engineering. With the advent of digital computers in the late 1950's, many power system analysis techniques had been computerized during the 1960's and early 1970's, with the development of sparse matrix algorithms a key advance [9]. Others included the Newton power flow [10], stochastic power flow [11], optimal power flow [12], the previously mentioned fast decoupled power flow [6], electromagnetic transient analysis [13], and power system reliability evaluation [14]. As noted in [15] many different power flow packages were being used in the industry, with solutions containing up to at least 4000 buses. While interactive computing was starting to appear [16], [17], most analysis was done with the input provided by punch cards or magnetic tapes.

In 1975 an important transmission control center development was starting to develop, what would become known as the energy management system (EMS) [18]. This was driven in part by the large 1965 North American blackout. The idea of an EMS is to provide a comprehensive electric transmission and generation control system that would be a combination of automatic and human initiated control [19], [20]. Building upon or replacing the existing SCADA, the EMS combined much of the existing monitoring and control of the transmission system with the AGC and with what would become known as network analysis functions. Key to this is the use of power system state estimation, an approach that had been presented in 1970 [21], [22], but would take decades to perfect.

Generation in 1975 was primarily either fossil fuels (coal, natural gas and oil) or hydro. Nuclear was starting to be used commercially, though not yet in large amounts. There was essentially no wind or solar generation. Transmission was almost exclusively ac with voltages up to 765 kV in North America [23], though the use of HVDC was increasing [24]. The application of power system stabilizers to damp oscillations was known, though they were not yet in widespread use [25]. Almost all of the power system protection was done using electromechanical relays, though digital relays were starting to appear [26]. A useful summary of the overall state-of-the-art for the electric grid at the end of 1974 is given in [27].

III. Survey Results

Building on the foundation of the grid from 1975, the focus here is on identifying the most impactful papers that helped create the grid of today. To achieve this, we surveyed members of the power system community using the survey approach described in the introduction.

1) Survey Limitations Before discussing the results, it is important to address the issues inherent in trying to determine the most impactful papers of the last 50 years. Like any survey the results are going to represent the opinions of the people who responded. While the survey was widely distributed and open to all, the responses are unlikely to represent a uniform sampling of electric power researchers and practitioners. In order to participate people needed to 1) know about the survey, and 2) have an interest in participating, 3) believe that they had sufficient knowledge of the publications over the last 50 years to provide useful input, and 4) be as unbiased as possible in their assessments. For distribution, several emails were sent out to over 10,000 people, mostly to electric power engineers or engineering students, with Power Globe [7] the single largest group. Of course, we are well aware that given the high email volume most people see, unsolicited emails can be easy to miss or ignore. On the interest and knowledge issue, given that individual papers are usually not discussed in a typical undergraduate curriculum, many practicing engineers probably do not know the specific origin of the ideas and algorithms that are embedded in the software that they use daily in their jobs. Hence the sample set would be naturally limited to people familiar with journal and conference papers.

On the issue of bias, a survey looking at the most impactful papers for the last 50 years is naturally going to represent the individual views of the respondents. To vote for a paper people need to know about the existence of the paper, which will naturally be somewhat biased by their area of expertise. In looking at the results it seems clear that most people didn't just vote for papers from their immediate colleagues. However, given that we only required two votes for inclusion, we cannot exclude the possibility that some of the entries may fall into this category. Nevertheless, we believe sufficient input was received to draw useful insights, particularly since responses included not just the papers but also comments on why they considered the papers so impactful.

2) Survey Results overall input was received from 76 people, with a total of 153 "votes" cast, recognizing that people could vote for up to three separate papers. Of this total, nine votes were eliminated either because they were the voter's own papers (three) or they referred to papers published before 1975 (six), including two votes for [28] from July 1974. This left a total of 144 votes for further evaluation. Mirroring the results from [2], ~20% of the respondents are affiliated with industry, while the remainder were mostly university professors or, in some instances, students. Most work in North America, though other continents were represented. Figure 1 shows the distribution of the votes by year of paper publication, with 39% before the year 2000, and 61% after. Of the 144 votes, 101 different publications were identified, with 18 receiving at least two votes. A summary of these 18 are shown in Table 1. The papers are ordered by year of publication, with complete citations given in the References section. The publication abbreviations are PAS (IEEE Transactions on Power Apparatus and Systems, published up to 1985), PWRS (IEEE Transactions on Power Systems, one of three journals that replaced PAS in 1986), EC (IEEE Transactions on Energy Conversion, another of the PAS replacements), and PAS 2002WM (IEEE Power & Energy Society 2002 Winter Meeting).

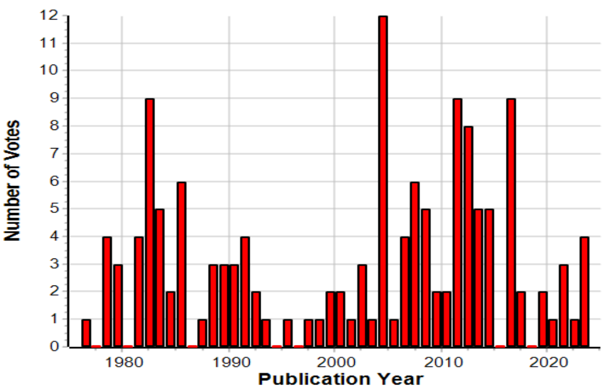

Figure 1: Votes by Year of Publication

IV. Analysis of Paper Themes

In analyzing the results several themes emerged. First, in considering Figure 1 and Table 1 there is not much of a correlation between years since publication and impact, other than noting that none of the most recent papers (2018 and after) got more than a single vote. Interestingly, papers published during the time period from 1992 to 2001 received very few votes. One explanation could be that this was a time in which the algorithms from earlier years were perfected. Another could be that this was a time in which there was little electric power research funding in many locations including the US.

A second theme is the vast majority of the papers have been published in IEEE journals, primarily PAS and then its successor PWRS. Just a few of the papers were in conference proceedings, and we were quite surprised that there were no votes for papers from the quite well regarded Power Systems Computational Conference (PSCC). While conference papers were more difficult to obtain in the past, this has changed with most papers now being relatively easily to obtain online; papers for all the PSCCs since 1966 are available open access at [29].

A third theme is the breadth of the responses. Of the 144 votes, most of the nominated papers received only a single vote. Some of this could be due to the sheer volume of papers now being published. In comparing the beginning of the 50-year period to the end, in 1975 the IEEE PES had one main publication, PAS, with a total page count of about 2200. In its last year of 1985 this had grown to 3700. In 2023 (the last year fully available) PES has seven journal publications with a total page count of more than 22,000. Given this volume and breadth of topics, it can be difficult for a single paper to stand out.

Table 1: Publications Receiving At Least Two Votes

Year	Authors	Topic	Publication	Votes
1979	Stott, Marinho [30]	Linear Programming Optimal Power Flow	PAS	2
1981	Bergen, Hill [31]	Stability Analysis	PAS	3
1982	Caramanis, Bohn, Schweppe [32]	Electricity Markets	PAS	6
1982	Verghese, Perez-Arriaga, Schweppe [33]	Selective Modal Analysis	PAS	2
1983	Phadke, Thorp, Adamiak [34]	Phasor Measurements	PAS	4
1985	Tinney, Chan Brandwajn [35]	Sparse Vector Methods	PAS	3
1988	Schweppe, Caramanis, Tabors, Bohn [36]	Electricity Markets	Kluwer	2
1990	Sauer, Pai [37]	Stability Analysis	PWRS	3
1991	Pereira, Pinto [38]	Hydropower Optimization	Mathematical Programming	3
2002	Lasseter [39]	Microgrids	PES2002WM	2
2004	Kundar, et. al. [40]	Stability Definitions	PWRS	4
2004	Wang, Nehrir [41]	DG Placement	PWRS	4
2006	Jabr [42]	Distribution grid optimization	PWRS	2
2008	Nehrir [43]	Wind/Solar	EC	2
2011	Zimmerman, Murillo-Sánchez, Thomas [44]	Power Flow Programs	PWRS	4
2012	Lavaei, Low [45]	Convex Relaxations of the OPF	PWRS	7
2016	Coffrin [46]	Convex relaxations of the OPF	PWRS	2
2017	Birchfield [47]	Synthetic Grids	PWRS	6

With respect to the Table 1 papers themselves, they can be grouped into nine main categories. These are 1) electricity markets, 2) power system optimization, 3) power system stability, 4) phasor measurements, 5) distribution systems, 6) microgrids, 7) numerical methods, 8) computer software, and 9) synthetic electric grids. We describe each category below, along with other themes observed among single vote papers.

1) Electricity Markets Electricity markets has two entries, with [32] a paper and then [36] a follow-up book. On the importance of this contribution respondees mentioned it as being "the seminal paper for modern electricity markets," as having real-world impact in the creation of electricity markets around the world and being "fundamentally transformative to the power industry during the last 30 years."

2) Power System Optimization Many of the nominated papers were associated with different aspects of power system optimization. Four papers were associated with advances in optimal power flow (OPF). While OPF had been described several years before 1975, development on improved algorithms and understanding is continuing up to the present. The oldest paper in this category, paper [30] from 1979, shows how the OPF can be solved using linear programming, with people noting its importance in providing fast solutions that have been widely used in practice. The other three OPF paper were related to convex relaxations of the AC OPF problem. Paper [42] is a two-page letter that gives an algorithm for solving the optimal power flow in radial distribution grid by treating it as a convex (in particular conic) optimization problem. The nominators recognize it as the paper that introduced convex relaxation of the optimal power flow. Paper [45], which received the most votes, "provides conditions under which the dual of the AC OPF problem would give the exact solution" and was "very influential in popularizing the idea of convex relaxations of the OPF problem", as noted by two nominators. People noted that this provides an "elegant structural insight and very practical algorithms to solving such large power system optimal power flow problems," and it inspired significant follow-on research. Paper [46] also considers OPF relaxations using a quadratic convex (QC) approach. One nominator noted a reason for selecting this paper it is extremely well written including excellent notation and an extremely understandable methodology and proof sections.

Optimization has improved power system operation and planning beyond OPF. For example, paper [38] described the use of stochastic dual dynamic programming (SDDP) for hydropower applications, and as one person noted this approach is "now in daily use in hydropower dominated power systems, including Norway, and Brazil".

3) Power System Stability Five papers related to power system stability were nominated. The first paper [31] is "a pioneering paper that provided a structure preserving approach to modeling large power system dynamics for stability analysis. The structure of the network is nicely preserved thanks to an innovative approach of modeling the loads. This opened door to many follow up work on decentralized control and stabilization for large power grids." This paper helped to lay the foundation for the use of control and systems theory in electric power systems that continues to the present. The second, a two part paper [33], lays the foundation for selective modal analysis that allows for the accurate and efficient calculation of poorly damped modes in an electric grid. Its results have been widely used in industry. Paper [37] helps in contributing to the theoretical understanding of power system stability, with one respondee noting its nice readability and educational style. The last paper in this category, [40], is noted as providing a very clear and unified understanding of power system stability terms that are useful both for research and practice. It is also one of the most highly citied power systems papers, with Google Scholar showing more than 5000 references.

4) Phasor Measurements Only one paper on phasor measurements [34] was nominated. The method of real-time phasor measurement and frequency tracking developed in this paper laid the foundation for modern synchrophasor technology that is now widely used throughout the industry. One person noted that the paper's results now play a vital role in improving power system monitoring, control and protection. A nice aspect of this paper also mentioned is that it provided not just theory, but also demonstrated its use in a utility laboratory installation.

5) Distribution Systems The next category broadly encompasses distribution systems with distributed generation and renewable applications. It contains three papers with [41] presenting an algorithm to the optimal placement of the growing number of distributed generation resources. In commenting on its significance, one person notes its high number of Google Scholar citations (more that 1500). Paper [43] presents a stand-alone wind/solar PV/fuel cell energy system. It is also quite highly cited (more than 1100) and is the only paper from EC. Paper [41], already discussed in the context of power system optimization, is relevant distribution grid optimization. While it only received a single nomination, it is also worthwhile to mention paper [48], which was nominated for proposing the elegant "DistFlow and DistFlow approximations that are central to most, if not all, algorithms for control, optimization, sensing, learning and distributed algorithms developed for distribution grids."

6) Microgrids The microgrid paper [39], which is the only conference paper in Table 1, has been foundational for defining the principles of Microgrid design, control, and operation. It conceptualizes practical Microgrid systems, which are now important for enhancing grid reliability, integrating renewable energy sources, and providing resilient power solutions for critical loads. It is also one of the mostly highly cited conference papers with more the 3800 in Google Scholar.

7) Numerical Methods While much of the foundational work in this area occurred before 1975, [35] was nominated for showing how sparse techniques that had been initially applied to matrices to solve $\mathbf{Ax} = \mathbf{b}$ could be extended to situations in which both $\mathbf{A}$ and $\mathbf{b}$ are sparse. The paper's techniques are now widely utilized throughout the electric power industry and many other industries as well.

8) Power System Software Packages A key development in many industries over the last 50 years have been the widespread application of commercial software. Whereas in 1975 many electric utilities and researchers developed their own power flow software, commercial packages became dominant over the next few decades. For example, the well-known PSS®E got its start in 1976 [49] and PowerWorld Simulator in 1994 [50]. This software, and many others, has had incredible impact on electric grid design and operation. However, most software packages are not documented in papers; when mentioned in publications the citation is to a user's manual or website. In contrast, [44] provides a useful description of the MATPOWER tool, which is an open-source, Matlab-based power system simulation package that provides power flow and OPF functionality. People noted a nice aspect is students could see efficient, yet clearly programmed reference implementations of power analysis algorithms. Reference [44] is actually the most cited PWRS paper, with more than 7500 references.

9) Synthetic Grid Models For many decades researchers, educators and software developers have used fictional (synthetic) electric grids for research, teaching, and developing new algorithms, such as the IEEE 118 bus case from the 1960's [51]. As models of actual grids have become more difficult to obtain due to security concerns, there is an even greater need for synthetic grids that are representative of modern grids but can be freely shared. Paper [47] presents algorithms for how creating such grids, including geographic information. In selecting this paper one person noted that is methods are crucial for developing new synthetic grids that can represent new generation and storage technologies that are being deployed.

10) Additional themes In presenting the Table 1 papers it is important to note that there are also many important papers and topics that weren't included in our discussion because they received just a single vote. While space prohibits a discussion of all of them, they do collectively cover some important topics that need to at least be mentioned. Grouped by topics the largest number of these single papers are associated with demand side management, with [52] a good example of how the load can be used as a control. A second important topic is the application of network reconfiguration, both in transmission [53] and distribution. Many other papers also focused on optimization methods for power systems, including contributions to e.g. stochastic optimization and unit commitment [54], [55], [56]. Electromagnetic transients is also a frequently mentioned topic, though there was no single paper getting more than one vote, no doubt because key papers such as [13] and [28] are from before 1975. Similarly, for power system stabilizers, only one person mentioning what we consider to be a key three-part paper from 1981 [25]. Other topic areas with multiple paper votes included voltage stability, HVDC, energy management systems (EMSs) including key applications, and cyber security.

V. Conclusion and Looking Forward

Since its first commercialization in the 1860's the use of electricity has transformed the world. While many of the key developments occurred before 1975, the last 50 years have been a time of both further development of these earlier ideas and a time of new innovation. With the help of input provided by many colleagues, this paper has presented some of the top works that have made these advancements possible. While the results of Table 1 speak for themselves, we want to end with our thoughts on the top papers of the last 50 years and some thoughts on the path forward. There are many things that could be said about the nominated papers, but more than anything, the selection demonstrates the wide range of topics and approaches that are needed to make the grid function at its best.

Looking forward the future is inherently uncertain, and as noted in [18] and [57], it is unlikely to be just an extrapolated view of the present. Research advances can alter the future, and blackouts and other unexpected events can dramatically affect the grid trajectory. Still several trends seem to be clear, at least for the next few years. While fossil fuels will be around for quite a while, generation sources are likely to continue to transition to more renewable sources such as wind and solar, supplemented with storage and perhaps nuclear and geothermal. As noted in [58], this will heighten the grid's dependence weather, making grid planning and operation more challenging. For example, the impact of renewable resource droughts [59] and impacts of the loss of system inertia also need to be considered [60]. Some initial directions to address the inclusion of weather in power system planning this are given in [61].

As these changes happen at the generation side, the demand side is also rapidly changing. At present the impact of artificial intelligence (AI) on the design and operation of the grid is unclear. Certainly, there are many situations in which AI can be used, and it seems clear that because of its high computational needs, its widespread application throughout society is going to continue to drive electric demand growth. The electrification of transportation, industry and residential heating is likely to contribute as well [62]. The transmission grid may experience increased deployment of grid enhancing technologies, and there is likely to be a dramatic expansion in the transmission capacity [63]. Overall, society's dependence on a reliable electric grid is likely to increase, meaning that blackouts will become increasingly costly. While they cannot be totally eliminated, reliability and resiliency will be key goals and areas for research. The need to mitigate what are called high impact, low frequency events will also continue to need to be a key focus [64], [65], [66].

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