Energy Informatics

RESEARCH Open Access

Electric grid reliability research

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Abstract

Background: Energy informatics (EI) is the area of research that addresses the application of technology to resolve complex problems in the energy domain. Goebel et al. (BISE 6:25–31, 2014) provided an EI research framework to encompass all aspects of EI research. Due to rapid EI improvements, many current research areas have not been incorporated into this framework. Specifically, this research posits that grid reliability is an underrepresented research area and should be incorporated into the framework. The rapidly changing nature of energy generation, and new developments in the electric-power network, are driving the need for grid reliability research. The goal of this paper is to extend the EI research framework offered by the Goebel et al. through a systematic review of current literature.

Methods: This literature review includes current publications (2015–2017) in power utility and technical reference libraries together with the earlier foundational EI papers.

Results: The systematic literature review is based on a broad automated search of appropriate digital sources (IEEE Xplore and the Web of Science) using relevant search terms. The paper also details the components of grid reliability research as well as their accompanying use cases.

Conclusion: The expanded EI research framework presented in this literature review should help researchers identify areas for future research endeavors. In the extended EI research framework, service reliability is now included as a third research component adding to the existing energy efficiency and renewable-energy supply components.

Keywords: Energy informatics, Grid reliability, EI research framework

Background

Energy informatics (EI) research concerns the use of information and communication technologies to address energy challenges (Watson and Boudreau 2011) and to inform the application of technology to resolve complex problems in the energy domain. The U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2017) classified challenges within the electricity-grid domain into two types: (1) transmission-system challenges and (2) distribution-system challenges. Transmission-system challenges include grid operations, grid reliability, grid stability, models and codes, grid operators, and utilities. Distribution-system challenges includes voltage and volt-ampere reactivity regulation, unintentional islanding, power quality, protection co-ordination, distribution modeling, visibility and control, codes, and standards.

Goebel et al. (2014) stated that energy efficiency and renewable-energy supply are the two principal types of research movements within the energy domain. Energy efficiency research involves studying individual incentives and behavioral dynamics to

influence electricity consumers' usage behavior. This first type drives the evolution of smart energy-saving systems. The second type of research, renewable-energy supply, seeks to resolve challenges arising in the integration of such renewable sources of energy as wind and solar power into the electric grid. This, in turn drives, the advancement of smart grids.

This research paper discusses an understudied research area within EI, grid reliability. Given the rapidly changing nature of energy generation, new developments of the electric power network, the incorporation of distributed energy resources into the grid, and circuit and equipment overloads, grid reliability research has been underwhelming. According to Goebel et al. (2014), energy efficiency and the renewable-energy supply are the two principal types of research movements in the energy domain. In their EI research framework, Goebel et al. considered grid reliability a subtopic, one of the many segments underlying the renewable-energy-supply research theme. Specifically, reliability was a segment under renewable-energy research. However, rapidly shifting challenges within the electric utility industry suggest that grid-reliability research should be classified as a new and separate area of research.

Grid reliability has several definitions. The North American Electric Reliability Corporation defined reliability as "the degree to which the performances of the elements of the electric system result in power being delivered to consumers within accepted standards and in the amount desired" (Hirst and Kirby 2000, p 7). Osborn and Kawann (2001) viewed reliability as "the ability of the power system components to deliver electricity to all points of consumption, in the quantity and with the quality demanded by the customer" (p 2). Reliability is measured by outage indices as illustrated by the Institute of Electrical and Electronics Engineers' Standard 1366. To facilitate a unified view of grid reliability, a definition is proposed: "the ability of the electric grid to deliver electricity to customers without degradation or failure." The argument is that today's power systems cannot accommodate, for instance, significant variable distributed energy generation without failure (U.S. Department of Energy 2015).

Grid reliability aims to address challenges and remove barriers to integrating high penetration of distributed-energy generation at the transmission and distribution levels (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy 2017). The subject includes many unaddressed questions: What makes the grid reliable? Why might reliability degrade? How do ongoing changes in grid use impose such a risk? What can we do to improve grid reliability? The U.S. Department of Energy has recently released its electric-grid reliability study, recommending prioritization of developments for grid resiliency and reliability (Profeta 2017). Additionally, in the same month, the U.S. Department of Energy, Office of Electricity announced an initial investment of nearly $900,000 to address power systems' risks and uncertainty, enabling academic research in the United States (Laezman 2017).

The goal of this paper is to restructure the Goebel et al. (2014) EI research framework through a systematic literature review to produce an updated framework highlighting grid-reliability research, all of its components, and its additional use cases.

The rest of the paper is organized as follows. The second section presents research importance. The third section describes the methodology used to conduct the systematic literature review. The fourth section outlines the results of the review, proposes an

enhanced EI framework, and presents a bibliography of foundational papers. Finally, the fifth section offers conclusions.

Research importance

Due to a rise in electricity use resulting from such new technologies as electric vehicles and circuit and equipment overloads, a significant number of publications from research organizations, governmental bodies, and utility companies have focused on understanding grid reliability, fault causes, and power outages. The National Academies of Sciences, Engineering, and Medicine (2017) recently published "Enhancing the Resilience of the Nation's Electricity System" in response to Congress's call for an independent assessment to "conduct a national-level comprehensive study on the future resilience and reliability of the nation's electric power transmission and distribution system." In addition, the National Academies of Sciences, Engineering, and Medicine established a committee to conduct the relevant research. Throughout this report, the committee highlighted all elements of grid reliability, resilience, and the risks of the system-wide failure that will grow as the structure of the power industry becomes more atomized and complex and laid out a wide range of actions to improve the U.S. power system's resilience. Analytics (including machine learning, data mining, and other artificial-intelligence techniques) will play a very important role in response to the predicted attacks on the electric grid, failures, or other impairments due to their ability to generate real-time recommendations (National Academies of Sciences, Engineering, and Medicine 2017).

In another exemplar research, Shawn Adderly (2016) examined U.S. Department of Energy's power outage data from 2002 to 2013 and investigated reliability trends. The research objective was to assess the correlation between utilities' reliability and grid-investment projects such as the deployment of smart-grid assets. Using the deployment of smart meters as a proxy for grid investments, Adderly concluded that the increase of smart meters correlated strongly with a decrease in the frequency of outages. The author acknowledged that due to the presence of confounding variables, the reduction in power outage could not be attributed to any specific smart-grid investment project.

Several studies attempt to understand grid reliability. Steve Mitnick's (2015) report prepared for the Electric Markets Research Foundation, another important resource, explains the reasons for concerns about grid reliability. The author suggests that distributed energy resources must be carefully incorporated into the grid to minimize grid-reliability risk. Another relevant study conducted by the Lawrence Berkeley National Lab (Eto et al. 2012) highlighted the fact that reliability-data trends might not improve due to the addition of smart-grid technology because automated outage-management systems may report service interruptions more accurately. Since the study was based on a sample of reliability data from several utilities, the authors did not attempt to make claims about overall U.S. power reliability.

With respect to the power-outage-causes study domain, the majority of the outages in the United States are the result of events that occur on the grid's distribution side. Few outages are caused by the external factors. The three main causes for electrical outages are (1) hardware and technical failures, (2) environmental incidents, and (3)

human errors. Among hardware and technical failures, outages are experienced due to equipment overload and short circuits, to name a few (Westar Energy 2017; Diesel Service and Supply 2017; Rocky Mountain Power 2017). These failures are often attributed to unmet peak demand, outdated equipment, and malfunctions of backup power systems (Chayanam 2005).

Environmental incidents, the largest portion of power outage causes, can be classified into two distinct categories: weather and other factors. Such publications as Wisconsin Public Service (2017) have highlighted the weather-related causes of power outages. The Edison Electric Institute states that 70% of U.S. power outages are weather related (as cited in Campbell 2012). Kenward and Raja (2014) analyzed power outage data over a 28-year period and noted that between 2003 and 2012, 80% of all outages were caused by weather. Similarly, Campbell (2012) highlighted the damage to the electrical grid caused by seasonal storms, rain, and high winds.

Besides weather, other external forces create power outages. As a byproduct of heavy weather patterns, falling tree branches disrupt the flow of electricity (National Academies of Sciences, Engineering, and Medicine 2017). Animals are another culprit of power disruption. The Edison Electric Institute study also indicated that animals, such as large birds, contacting power lines accounted for 11% of U.S. outages (as cited in Campbell 2012).

Human-error incidents are the last cause of power outages. Chayanam (2005) indicated that training is essential for technicians and staff to battle outages with proper maintenance procedures. This ensures a reduction in the frequency of power outages. Car accidents are another major source of power outages (Wisconsin Public Service 2017).

In a 2013 white paper entitled "the Smart Grid Investment Grant Program Progress Report," the Department of Energy highlighted reliability improvements observed through decreasing reliability indices and highlighted that such projects as automated feeder switching were able to reduce the frequency of outages. No statistics were shown in the report to demonstrate the correlation between reliability indices and spending. However, the study identified the progress made by utilities as a result of receiving federal funding (U.S. Department of Energy 2013).

Interrupted power supply is no longer a mere inconvenience. As the duration and spatial extent of electrical outages increases, costs and inconvenience grow. Critical social services such as medical care, police and other emergency services, and communications systems rely upon electricity to function at minimally acceptable levels. Failures can bring catastrophic outcomes; lives can be lost. We must better understand the causes to be more ready to implement redundancy and resilience in the electric grid.

To heed this call, this paper presents a systematic grid-reliability literature review to help understand the topic's current knowledge base. A systematic literature review is a particularly influential tool in the hands of researchers because it allows a scholar to gather and recap all the information about research in a specific field (Spanos and Angelis 2016). In this first systematic grid-reliability literature review, the focus is on the different grid-reliability topics and their specific characteristics. This article should enrich future literature reviews while integrating the most current articles into the body of knowledge.

Methodology

The systematic literature review offered in this paper follows the three stages in a systematic review: the Planning Stage, the Conducting Stage, and the Reporting Stage (Kitchenham 2004; Kitchenham and Charters 2007).

The first step is the identification of a need for a systematic review. As described in the previous two sections, although several studies have investigated electric-grid reliability, these studies should be summarized to update the current knowledgebase. Therefore, the urgent need for a systematic literature review providing solid foundations and equipping researchers with pertinent information is clear.

The second step is the development of the review protocol. This section presents the research questions, search strategy, inclusion/exclusion criteria, quality-assessment criteria, and the data extracted from the studies.

Defining research questions is an essential step in every systematic review. By answering the following questions, the literature review can accomplish its aim.

1. How many research studies have examined electric-grid reliability?
2. What are the types of reliability-research questions?
3. What are the studies' results?
4. What research methods are used?

To conduct the systematic literature review, it was decided to do a broad automated search, a method that includes the selection of the most appropriate digital sources (digital libraries and indexing systems) and the determination of the search terms (Spanos and Angelis 2016). The digital libraries of IEEE Xplore and the Web of Science were selected for the systematic review. The Web of Science database provides a wide breadth and depth, whereas the IEEE database provides more narrowly focused and very recent research. These searches relied on papers' titles to avoid receiving duplicate or irrelevant papers as search results. The following search strings were used.

IEEE Xplore Boolean/Phrase

(((((“Document Title”:Electricity Reliability) OR “Document Title”:Electric Grid Reliability) OR “Document Title”:Power System Reliability) OR “Document Title”:Electric Circuit Reliability) OR “Document Title”:Power Outage Research)

refined by.

Content Type: Conference Publications Journals & Magazines Books & eBooks Year: 2015–2017

The year range is limited to those 3 years to ensure the search captures the reliability impact of integrating distribution-energy resources into the electric grid.

Web of Science Boolean/Phrase

TITLE:(Electricity Reliability) OR TITLE:(Electric Grid Reliability) OR TITLE:(Power System Reliability) OR TITLE:(Electric Circuit Reliability) OR TITLE:(Power Outage Research) AND TITLE: (“estimate*” OR “assess*”)

refined by.

DOCUMENT TYPES: (PROCEEDINGS PAPER OR ARTICLE)

Timespan: 2015–2017. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI.

The inclusion/exclusion selection criteria of any systematic literature review must be distinct and clearly stated (Spanos and Angelis 2016). The following selection criteria were used for the systematic review.

1. Full-article publication (not just an abstract),
2. English-language publication,
3. Year of publication sufficiently recent (since year 2015) to ensure that the reliability impact of integrating distribution energy resources into the electric grid has been captured, and
4. Study relevance.

The following exclusion criterion was used.

1. Duplicate publications (to avoid double counting studies)

The quality-assessment criteria are provided to ensure that all the included studies in a systematic literature review contain an adequate level of quality. The following were the criteria.

- Availability and the description of the data,
- Description of the used methodology, and
- Presentation of the results.

The last task is related to the development of the review protocol and the selection of the data features that will be extracted from the papers found by the search. The data features for this review are as follows.

- Author(s),
- Year of publication,
- Type of paper,
- The research question(s),
- Method(s) used, and
- Result(s).

Results

This section presents the initial results of the systematic literature review: 209 papers from the IEEE Xplore database and 294 papers from the Web of Science core collection. Table 1 summarizes the characteristics of the documents identified and the counts of papers by year.

The top publishing authors were M Fotuhi-Firuzabad (10 publications), C Singh (8), LF Wang (8), YM Xing (8), and M Benidris (6).

After the excluding duplicate, irrelevant, and low-quality papers, 231 papers remained from the search in the two databases. Table 2 summarizes the search results (503 total paper count from the initial search), the number of non-relevant, the duplicate papers,

Table 1 Study characteristics

	IEEE Xplore	Web of science
Paper type		
Proceedings and conferences	152	164
IEEE conference publications	146	
IET conference publications	5	
VDE conference publications	1	
Journals and magazines	57	132
CPSS journals and magazines	1	
IEEE journals and magazines	40	
IET journals and magazines	16	
Total	209	296
Year		
2015	66	111
2016	95	122
2017	48	61
Total	209	294

those not-included after the quality assessment, and the final number of relevant papers included in the systematic literature review for analysis.

Preliminary analysis of the relevant papers identified four key types of research question:

1. How does one assess or evaluate reliability of the power grid?
2. How does one improve or enhance the reliability of the electric-power system?
3. How should one plan reliability of the smart grid?
4. What are the impacts of changes, including adding distributed-energy resources, new regulations, and investment projects, on the reliability of the electric-power system?

Research methods within this research domain can be classified either as analytical or as Monte Carlo simulation. Analytical techniques represent the system by a mathematical model and evaluate the reliability indices from this model using mathematical solutions. Monte Carlo simulation methods, on the other hand, estimate the reliability indices by simulating the actual process and the system's random behavior. Simulation treats problems as a series of real experiments. There are advantages and disadvantages to both methods.

Table 2 Database search results

Database criteria	IEEE Xplore	Web of science	Total count
Number of papers found as a result of the search	209	294	503
Irrelevant papers	42	41	83
Duplicate papers	7	173	180
Papers not included due to inadequate quality	4	2	6
Not an English-language publication	2	1	3
Final number of relevant papers	154	77	231

The foremost research methods are modeling and simulation. Simulation modeling is the process of creating and analyzing a prototype of a physical model to predict its performance in the real world. Simulation modeling is used to help researchers understand whether, under what conditions, and in which ways a part could fail and what loads it can withstand. Researchers have used various modeling and simulation tools to perform the analysis, but Monte Carlo simulation is the most dominant research method.

Based on the systematic literature review, the Goebel et al. (2014) EI research framework was extended. The following section illustrates the impact of this extension and highlights the addition of grid reliability research, all of its components, and its use cases.

Energy informatics enhanced research framework

In the proposed Energy Informatics enhanced research framework (Fig. 1), energy efficiency, renewable-energy supply, and service reliability are the three types of research streams in the energy domain. These streams reflect the topics identified in the systematic literature review. The restructured Goebel et al. (2014) framework includes service reliability as a third research stream in addition to energy efficiency and the renewable-energy supply to distinguish this understudied research area. The first theme, energy efficiency, drives the evolution of smart energy-saving systems. The second theme, renewable-energy supply, drives the advancement of smart grids. Finally, the third additional theme, service reliability, drives smart-grid reliability and resiliency.

In the context of the service-reliability research theme, use cases (a collection of possible scenarios) were classified into four transmission scales: subcontinental, regional,

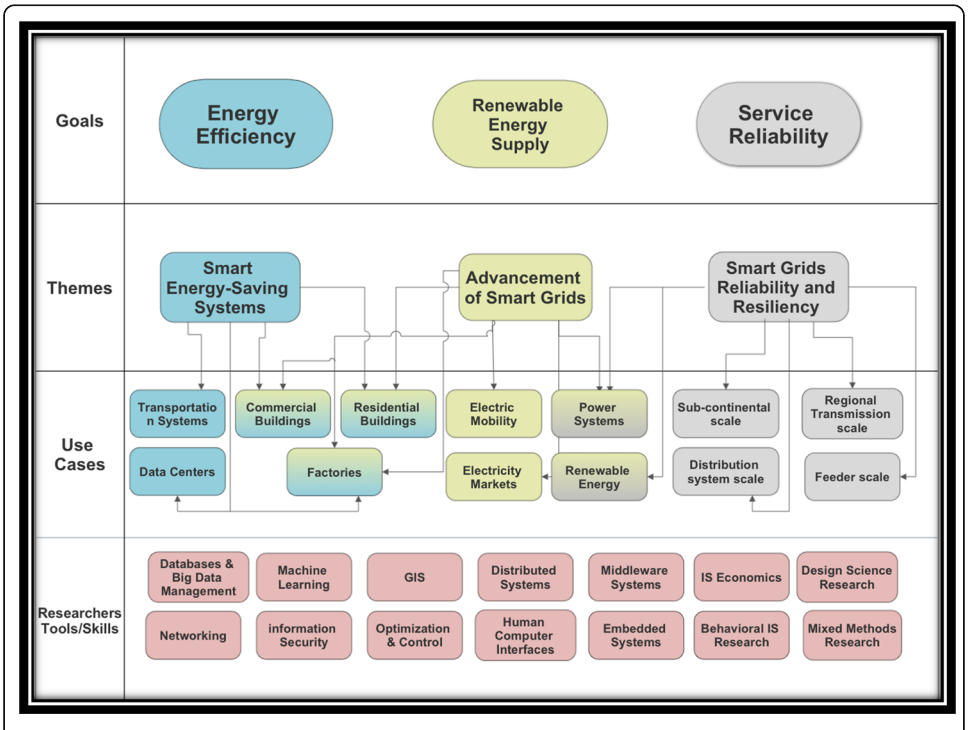

Fig. 1 Energy informatics enhanced research framework—Enriched with reliability research

local distribution system, and feeder. Power systems and renewable energy can also be viewed as additional use cases due to their impact on grid reliability. The rapidly changing nature of energy generation and the new developments of the electric power network have fueled the rise of grid-reliability research to justify considering it a separate research stream.

The first category of use cases, the subcontinental scale, examines large, relatively self-contained landmasses forming a subdivision of a continent. Within this category, multiple grids, transmission, and distribution systems may exist and be interconnected.

In the second category of use cases, regional transmission, studies examine high-voltage transmission networks that enables power to travel long distances from generating units to substations closer to local end-use customers where the voltage is stepped back down and sent into the distribution system for delivery to consumers. Given the interconnected configuration of the high-voltage grid, events in one place can propagate across the transmission system in seconds or a few minutes, potentially causing cascading blackouts that can affect customers hundreds of miles from the initial disturbance. Outage events on the transmission system can result in large-area impacts (National Academies of Sciences, Engineering, and Medicine (2017).

In the third type of use cases, the electric distribution system moves power from the energy system to the meters of electricity customers. Typically, power is delivered to distribution substations from two or more transmission lines, where its voltage is reduced, and sent to customers over distribution feeders. Although distribution-system outages are more common than those occurring on transmission facilities, their impacts are smaller in scale and generally easier to repair (National Academies of Sciences, Engineering, and Medicine 2017).

The fourth category of use cases includes the feeder scale. Customers on radial systems are exposed to interruption when their feeder experiences an outage. In metropolitan areas, these feeders typically have switches that can be reconfigured to support restoration from an outage or regular maintenance. When a component fails in these systems, customers on unaffected sections of the feeder are switched manually or automatically to an adjacent, functioning, circuit. However, this still exposes critical services such as hospitals or police stations to potential outages, so these facilities are often connected to a second feeder for redundancy (National Academies of Sciences, Engineering, and Medicine 2017).

The definition of service reliability—"the ability of the electric grid to deliver electricity to customers without degradation or failure"—is used to outline the service-reliability research theme. Recent developments such as the integration of distributed-energy resources into the smart grid make information collection, integration, management, and analysis of vital importance. That is why EI has flourished in the research community.

Here, the aim is to contribute to a holistic understanding of problem identification and resolution through the use of tools such as geographic information systems, databases, big-data management, machine learning, information security, and optimization and control. Analytics using these tools could transform the way we think, act, and use energy and help elucidate a problem's root cause, define a solution through data, and implement the solution with continuous monitoring and management.

Power-system reliability research framework

In addition to the EI enhanced research framework, Fig. 2 illustrates a framework for power-system reliability founded on the previous literature. The focus within the power-system-reliability research theme can be organized into one of two main types: the bulk-power system (BPS) and the local-distribution system. The first research focus, can be defined as a large interconnected electrical system made up of generation and transmission facilities and their control systems. A BPS does not include facilities used in the local distribution of electric energy. If a BPS is disrupted, the effects are felt in more than one location. In the United States, BPS are managed by the North American Electric Reliability Corporation (National Academies of Sciences, Engineering, and Medicine 2017). Reliability of power supply and system operation, regular evaluations of expected or emerging changes, and system maintenance throughout changes in the electric industry are all possible goals within the BPS research focus.

The local-distribution system, the second research focus, provides power to individual consumer premises. Distribution networks usually consist of distribution substations, primary distribution feeders, distribution transformers, distributors, and service mains (National Academies of Sciences, Engineering, and Medicine 2017). Maintenance and repair of the distribution network, public safety, and operating cost are the possible goals within the local-distribution system research focus.

The combined transmission and distribution network is known as the "power grid" or simply "the grid." North America's BPS involves four different power grids (interconnections). The Eastern Interconnection serves the eastern two thirds of the continental United States and Canada from the Great Plains to the Eastern Seaboard. The Western Interconnection covers the western third of the continental United States, the Canadian provinces of Alberta and British Columbia, and a portion of Baja California Norte in Mexico. The Texas Interconnection includes most of the State of Texas. Finally, the Canadian province of Quebec is served by the fourth North American interconnection.

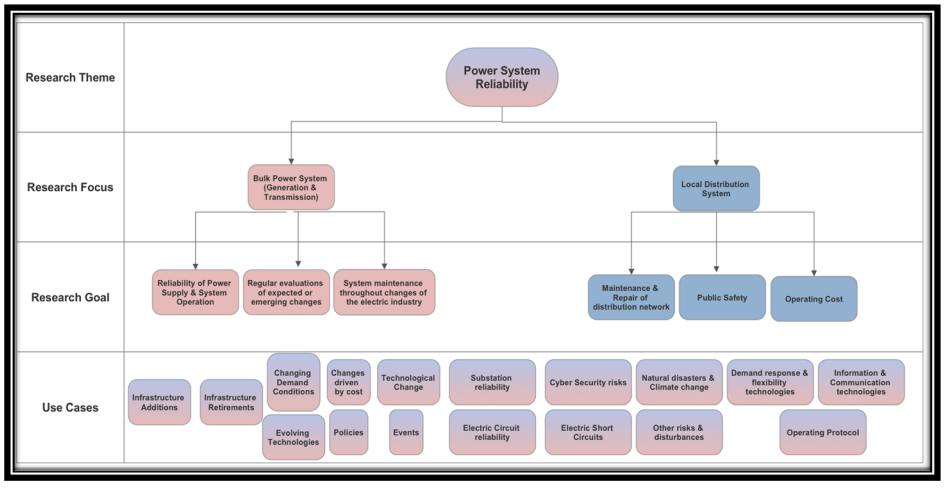

Fig. 2 Power-system reliability research framework

The grid systems in Hawaii and Alaska are not connected to the grids in the continental states (U.S. Department of Energy, Office of Electricity 2015).

In the context of the power-system reliability research theme, possible scenarios, or use cases, can be classified into: infrastructure addition, infrastructure retirement, changing demand conditions, evolving technologies, changes driven by cost, policies, technological change, events, substation reliability, electric-circuit reliability, electric short circuits, cybersecurity risks, natural disasters and climate change, demand response and flexibility technologies, information and communication technologies, operating protocol, and other risks and disturbances.

Foundational papers on the subject of electric-grid reliability

One way to grasp the main core of a subject is to look at the references cited in the current articles and highlight papers that are continually referenced. This step was particularly helpful in identifying the foundational papers.

The same search string was used without an exclusion criterion (no year range restriction) to pull all journal and magazine publications from the database. The results (366 extracted articles) were sorted in descending order based on the number of citations (the number of other papers' reference lists that included them), the standard deviation for each article's number of citations was calculated, and the outliers (articles whose number of citations was more one standard deviations) were identified. Based on this analysis, 59 foundational papers were identified. After excluding the irrelevant papers and those not meeting the quality criteria, 39 relevant papers remained (Table 3).

This section presents a bibliography and the analysis of foundational papers on the subject of electric-grid reliability (Table 4).

Table 5 summarizes the research methods identified in the foundational papers. Though modeling and simulation are dominant research methods within the literature, articles using analytical approaches seem to be gaining more attention considering how often they are cited.

Bearing in mind the research themes and the methods illustrated in the foundational papers, analytics has been a popular topic in research and more research is needed in the area of reliability planning and improvement, particularly in the energy field. Through the use of GIS, machine learning, and data-mining techniques, analytics would help the research community plan and improve the smart grid.

Table 3 Foundational paper statistics

Database criteria	Total count
Journal and magazine papers found by the search	366
Standard deviation for the articles' citation counts	30
Articles whose # of citations exceeded one standard deviation (30 citations)	53
Irrelevant papers	10
Papers not included due to inadequate quality	4
Final number of relevant anchor papers	39

Table 4 Foundational papers in electric-power-supply reliability

Document title	Authors	Year	Cite count	Research question	Research method	Research result
A test system for teaching overall power system reliability assessment	R. Billinton; S. Jonnavithula	1996	186	How does one evaluate overall power-system reliability using an educational test system?	Modeling & Simulation: This paper illustrates how reliability indices can be predicted and provides an overall test system that can be used in graduate or undergraduate settings to illustrate the calculation of these indices.	This paper presents a basic electric-power system network that can be used in teaching overall power-system reliability assessment. The paper introduces the concept of overall assessment, which deals with actual customer levels of service. This is an important requirement in today's changing utility environment and one that should be stressed in teaching reliability concepts.
Probabilistic evaluation of the effect of maintenance on reliability. An application [to power systems]	J. Endrenyi; G. J. Anders; A. M. Leite da Silva	1998	134	How does one provide a quantitative connection between reliability and maintenance in power systems?	Quantitative: The component aging process is modeled, and the mean and distribution of the remaining life to failure are predicted for any stage of aging. The method is applied to a practical example.	This paper proposes a probabilistic model for the purpose and describes a computer program based on this model. The model provides a quantitative connection between reliability and maintenance, a link missing in the heuristic approaches.
A reliability-centered asset maintenance method for assessing the impact of maintenance in power distribution systems	L. Bertling; R. Allan; R. Eriksson	2005	126	How does one assess the impact of maintenance in power-distribution systems?	Quantitative: A systematic approach is presented for investigating the effect of different maintenance strategies. In particular, the authors develop a functional relationship between failure rate and maintenance measures for a cable component.	This paper proposes a method for comparing the effect of different maintenance strategies on system reliability and cost. This method relates reliability theory with the experience gained from statistics and practical knowledge of component failures and maintenance measures. The results show the value of using a systematic quantitative approach to

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
						investigate the effect of different maintenance strategies.
Sequential Monte Carlo simulation for composite power system reliability analysis with time varying loads	A. Sankarakrishnan; R. Billinton	1995	99	How does one assess reliability in a composite generation-and-transmission system?	The authors suggest a sequential Monte Carlo simulation for composite power system reliability analysis with time varying loads. They apply antithetic variates, as a variance reduction technique, to the simulation model to increase its simulation efficiency. They apply an approximate method using a system-load duration curve and an enumeration process to the developed load model and compare the results.	The paper illustrates the development and utilization of an annual chronological load curve for each load bus in a composite generation-and-transmission system and a sequential Monte Carlo simulation approach for composite system-reliability assessment.
Power system reliability I-measures of reliability and methods of calculation	D. P. Gaver; F. E. Montmeat; A. D. Patton	1964	92	How does one calculate reliability in general power-system networks?	The authors present a probability method that permits important measures of reliability in general power-system networks to be calculated from basic system component data. The reliability of an alternative proposed system can be compared to discover the system yielding the highest reliability or a desired reliability at lowest cost. Important features of the method of the paper include the ability to consider failure bunching caused by storms and outages as a result of	This paper presents some basic concepts of the physical significance of various aspects of probability methods as applied to power-system generating-capacity problems. It also discusses the physical meaning and interrelation of various standards of service reliability and the determination of the installed capacity benefits of an interconnection by means of the application of probability method, which can serve as a tool for measuring the reliability performance of an electric-power system, thus

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
					component overloading in parallel systems.	providing sound basis for judging when additional facilities are needed.
A Canadian customer survey to assess power system reliability worth	G. Tollefson; R. Billinton; G. Wacker; *E. Chan*; J. Aweya	1994	91	How does one quantify the value or benefit of electric-service reliability?	Quantitative: A common approach used in quantifying the value or benefit of electric-service reliability is to estimate the customer costs (monetary losses) associated with power interruptions. Customer surveys are used to determine interruption costs.	The IEEE Power Systems Research Group has conducted surveys of Canadian electric-utility customers in the residential, commercial, and industrial sectors, sponsored by the Natural Sciences and Engineering Research Council and seven participating utilities. This paper presents the overall results of these surveys with emphasis on the cost results.
A security based approach to composite power system reliability evaluation	R. Billinton; E. Khan	1992	91	How does one evaluate reliability of a composite power system using a security-based approach?	Linear programming model: The authors classify the composite system into different system states and calculate probabilistic indices for each. Using both annualized and annual indices in a seven-step load model of two test systems, the authors detect problem-creating contingencies and present a linear programming model for generation rescheduling and minimization of the amount of load shed.	An electric power network containing generation and transmission facilities can be divided into several states in terms of the degree to which adequacy and security constraints are satisfied in a reliability evaluation of the composite system. The authors present a linear programming model for generation rescheduling and load-shed minimization. A linear programming model for correcting the voltage problem is presented.
Reconfiguration of power distribution systems considering reliability and	B. Amanulla; S. Chakrabarti; S. N. Singh	2012	90	How does one reconfigure power distribution systems considering reliability and	Using probabilistic reliability models, the authors evaluate reliability at various load points	The paper develops a power-distribution-system reconfiguration methodology

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
power loss				power loss?	with an algorithm to find the minimal set of components appearing between the feeder and any particular load point.	considering the reliability and the power loss. The paper presents the optimal status of the switches to maximize the reliability and minimize the real power loss by a binary particle-swarm-optimization-based search algorithm. The proposed methodology's effectiveness is demonstrated on 33- and 123-bus radial distribution systems.
An efficient technique for reliability analysis of power systems including time dependent sources	C. Singh; Y. Kim	1988	87	How does one analyze reliability of electric-power systems with such time-dependent sources as photovoltaic and wind generation?	Analytical model: The authors' method proposed groups the units into several subsystems. One subsystem contains the conventional units and the remaining subsystems consist of unconventional units. A generation system model is built for each subsystem. The outputs for the unconventional units and the load are treated as correlated random variables. The authors use a clustering procedure to identify states with, for a given value of load, specific mean values of the outputs from the unconventional units.	The paper introduces a method of reliability analysis for electric-power systems with such time-dependent sources as photovoltaic and wind generation. The fluctuating characteristic of unconventional generation units has a different effect on the reliability of the generation system than do conventional units. The paper presents reliability analysis combining the conventional subsystem with the unconventional subsystems in each state and combines the output from all the states to compute the loss of load expectation and expected unserved energy.
A reliability model of large wind farms for power system adequacy studies	A. S. Dobakhshari; M. Fotuhi-Firuzabad	2009	73	How does one model the reliability of large wind farms for power-system adequacy studies?	The paper proposes a systematic method based on a frequency-and-duration approach to model a wind farm as a multistate conventional	This paper presents an analytical approach to reliability modeling of large wind farms. The results show that seasonal patterns

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
					unit: The probability, frequency of occurrence, and departure rate of each state can be obtained using the wind farm's regional wind regime and wind turbine characteristics. The proposed method can find both annual frequency and average time of load curtailment analytically in the presence of wind power. As an example, the paper studies a wind farm in northern Iran with 1 year of wind speed data.	significantly affect the reliability indices. A reliability analysis using a load profile similar to that of Iran's power network shows that the coincidence of high-load-demand and high-wind-speed periods makes the northern Iran wind-farm projects highly attractive from a reliability point of view. The paper includes reliability analysis considering seasonal patterns of wind speed to accommodate time-varying wind-speed patterns.
Power distribution system planning with reliability modeling and optimization	Y. Tang	1996	70	How does one plan a power distribution system with reliability modeling and optimization?	Modeling and optimization: The paper models distribution-system reliability in the optimization objective function via outage costs and costs of switching devices, along with the nonlinear costs of investment, maintenance and energy losses of both the substations and the feeders.	Supported by an extensive database, the planning software tool can optimize the power-distribution system of a developing city. The optimization model established is multistage, mixed integer and nonlinear solved by a network-flow programming algorithm. The paper also presents a multistage interlacing strategy and a nonlinearity iteration method.
Cost–benefit analysis of power system reliability: Two utility case studies	E. G. Neudorf; D. L. Kiguel; G. A. Hamoud; B. Porretta; W. M. Stephenson; R. W. Sparks; D. M. Logan; M. P. Bhavaraju; R. Billinton; D. L. Garrison	1995	64	How does one do cost–benefit analysis of power-system reliability?	A cost–benefit approach that quantifies the reliability benefits of alternatives in terms of the reduction in costs resulting from unserved energy enables the evaluation of generation and transmission	This approach is applied to two utility case studies. For the Pacific Gas and Electric Company, it was used to evaluate three options for maintaining reliability in a major load center—two

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
					capacity additions on a consistent, economic basis.	involving local generation, and a third employing a new 230 kV transmission connection. For Duke Power Company, the approach was used to evaluate alternative designs for additions to a transmission station.
Frequency and duration methods for power system reliability calculations: I-generation system model	J. D. Hall; R. J. Ringlee; A. J. Wood	1968	62	How does one evaluate and compute electric-power-system reliability considering the requirement that a consistent technique be used for all portions: generation, transmission, and distribution?	This paper is concerned with the procedure for calculating the availability, frequency, and outage duration for a number of generating units connected in parallel to form a single system.	A reliability-calculation method for the generation system that incorporates the frequency and duration of unit outages and includes consideration of the loads leads to three calculated generation-reliability measures: availability, frequency of occurrence, and mean duration of reserve states. These are cumulative states in that they specify system reserve conditions of a given magnitude or less. Numerical data are used to illustrate the technique and compare with other methods.
Population-based intelligent search in reliability evaluation of generation systems with wind power penetration	L. Wang; C. Singh	2008	60	How does one assess power-generating systems to ensure proper system operations in the face of various uncertainties including equipment failures?	Mixed method: Four representative population-based intelligent search procedures—genetic algorithm, particle-swarm optimization, artificial-immune system, and ant-colony system—are adopted to search the meaningful system states through their inherent convergence mechanisms. These most-	Due to the large number of system states involved in system operations, to enumerating all possible failure states to calculate the reliability indices is not normally feasible. Monte Carlo simulation can be used for this purpose through iterative selection and evaluation of system states. However, due to

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
					probable failure states contribute most significantly to the adequacy indices including loss-of-load expectation, loss-of-load frequency, and expected unmet demand. The proposed solution methodology is also compared with the Monte Carlo simulation through conceptual analyses and numerical simulations with some qualitative and quantitative comparisons.	its dependence on proportionate sampling, its efficiency in locating failure states may be low. The simulation may thus take a long time to converge in some evaluation scenarios. This investigation uses a modified IEEE reliability test system is used.
Reliability evaluation of generating systems containing wind power and energy storage	P. Hu; R. Karki; R. Billinton	2009	51	How does one evaluate the reliability of generating systems containing wind power and energy storage?	The paper presents a simulation technique that can consider wind-farm and energy-storage operating strategies, evaluates different operating strategies are compared and the resulting benefits, and illustrates the system impacts of energy storage capacity and operating constraints, wind-energy dispatch restrictions, wind penetration levels, and wind-farm location on the reliability benefits from energy storage.	High wind penetration can lead to high risk levels in power-system reliability and stability. Maintaining system stability may require wind-energy dispatch restrictions and energy storage to smooth out the fluctuations and improve supply continuity. The benefits from using energy storage are highly dependent on the operating strategies associated with wind and storage in the power system.
System reliability assessment method for wind power integration	F. Vallee; J. Lobry; O. Deblecker	2008	49	How does one assess system reliability for wind-power integration?	Modeling: A new method, based on a discrete convolution process, to compute a *two-state* global probabilistic model for wind generation and to define an equivalent capacity for global wind production and	It is illusory to imagine that all the installed wind capacity will always be productive. This convolution between each single wind park and multistate histograms permits the accurate computation of equivalent capacity for an

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
					introduce it in the predictive peak-load covering process.	entire country's wind production.
Bibliography on the application of probability methods in power system reliability evaluation	R. N. Allan; R. Billinton; A. M. Breipohl; C. H. Grigg	1999	46	What has been published on the subject of power-system reliability evaluation?	This paper presents a literature review and bibliography of papers on the subject of power-system reliability evaluation up to year 1999.	
Discrete convolution in power system reliability	R. N. Allan; A. M. Leite da Silva; A. A. Abu-Nasser; R. C. Burchett	1981	45	How does one evaluate power-system reliability?	The paper presents a method for convolving discrete distributions using fast Fourier transforms to evaluate a generating system's loss-of-load probability and demonstrate the method's application and inherent merits.	This method can be used in evaluating reliability of any system involving discrete or discretized convolution. It has been used in power-system studies to deduce capacity-outage probability tables and to solve probabilistic load flows. This method is much less time-consuming and more efficient than the conventional direct methods.
Critical component identification in reliability centered asset management of power distribution systems via fuzzy AHP	P. Dehghanian; M. Fotuhi-Firuzabad; S. Bagheri-Shouraki; A. A. Razi Kazemi	2012	44	How does one determine the most critical component types of power-distribution systems to be prioritized in maintenance scheduling?	A practical case study using the proposed fuzzy analytical hierarchical process method introduces its applicability and efficiency in the asset management.	This paper presents a novel approach on the basis of the analytical hierarchical process accompanied by fuzzy-set theory to determine the most critical component types of power-distribution systems to be prioritized in maintenance scheduling. In the presence of many qualitative and quantitative attributes, fuzzy sets can effectively help to deal with the existent uncertainty and judgment vagueness.
An information architecture for future power systems and	Z. Xie; G. Manimaran; V. Vittal; A. G. Phadke; V. Centeno	2002	44	What information architecture should we use for future	Modeling: Modeling real-time operating and control system	This paper points out the major deficiencies in current

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
its reliability analysis				power systems, taking into account the requirements of real-time data, security, availability, scalability, and appropriate quality of service?	with various redundancy configurations facilitates the study of the reliabilities of different configurations and the comparison of practical values of component failure rates and repair rates.	communication and information systems and proposes a new power-system information architecture aimed at correcting these deficiencies. The proposed architecture includes automation and control systems at all levels, from substation control system to independent-system-operator operating center. It uses multiple communication channels employing a wide variety of technologies to transmit real-time operating data and control signals.
Incorporating aging failures in power system reliability evaluation	W. Li	2002	43	How does one incorporate aging failures in power-system reliability evaluation?	This paper uses a calculation approach with two possible probability distribution models to evaluate unavailability of aging failures and implementation reliability. The BC Hydro North Metro system serves as an example to demonstrate an application of the proposed method and models.	The results indicate that aging failures have significant impacts on system reliability, particularly for an "aged" system. Ignoring aging failures in reliability evaluation of an aged power system will result in an underestimation of system risk and most likely a misleading conclusion in system planning.
Bayesian network model for reliability assessment of power systems	D. C. Yu; T. C. Nguyen; P. Haddawy	1999	43	How does one apply Bayesian networks to resolve the problem of power-system reliability assessment?	A Bayesian-network probabilistic inference algorithm not only permits computation of the loss-of-load probability, but also answers various probabilistic queries about the system. Examples demonstrate the advantages of Bayesian-network models for power-	Results of a reliability case study of a multiarea test system demonstrate that Bayesian networks provide a flexible means of representing and reasoning with probabilistic information, easily incorporating uncertainty and dependencies in the analysis.

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
					system reliability evaluation.	
Latin hypercube sampling techniques for power systems reliability analysis with renewable energy sources	Z. Shu; P. Jirutitijaroen	2011	41	How does one conduct reliability analysis of power systems including renewable energy sources, with an emphasis on the fluctuation of bus loads and intermittent behavior of such renewable sources as wind and solar power?	This paper compares Monte Carlo sequential sampling, Monte Carlo nonsequential sampling, and from the proposed Latin hypercube sampling. Two case studies modified from the Electric Reliability Council of Texas and IEEE Reliability Test System demonstrate the proposed sampling methods' performance.	This paper proposes Latin hypercube sampling methods for reliability analysis of power systems including renewable energy sources, with an emphasis on the fluctuation of bus loads and intermittent behavior of such renewable sources as wind and solar power. The proposed methods are as accurate as the other sampling methods while using much less CPU time.
Evaluating future power distribution system reliability including distributed generation	M. Al-Muhaini; G. T. Heydt	2013	41	How does one assess the impact of conventional and renewable distributed generation on the reliability of future distribution systems?	Modeling: The paper models and studies the stochastic nature of renewable resources and their influence on the reliability of the system by computing the adequacy transition rate and proposes an integrated Markov model that incorporates the distributed-generation adequacy transition rate, distributed-generation mechanical failure, and starting and switching probability to give accurate results for the distributed-generation reliability assessment.	This paper assesses the impact of conventional and renewable distributed generation on the reliability of future distribution systems, even when the connection may not be simply radial. The technique used appears to be applicable to any renewable energy source.
Frequency and duration methods for power system reliability calculations: ii - demand model and capacity	R. J. Ringlee; A. J. Wood	1969	40	What frequency and duration methods can be used for power-system reliability calculations?	Incorporating a model of the power system load with the generation-system model developed previously permits	This paper incorporates a model of the power-system load in the generation-system model developed previously.

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
reserve model					computation of the availability, frequency of occurrence, and mean duration of generation reserve, or margin states. This work illustrates its results with by continuing a simple numerical example.	Previous methods yield only the availability of the reserve margin states, or else availability and frequency data for generating-capacity states without considering the load. The method presented and illustrated may be extended to calculate operating reliability or the inclusion of the effects of a simple transmission system.
Improving power system reliability calculation efficiency with EPSO variants	*V. Miranda*; L. de Magalhaes Carvalho; M. A. da Rosa; A. M. Leite da Silva; C. Singh	2009	39	Can one use such population-based methods as evolutionary particle-swarm optimization to evaluate power-system reliability?	This paper uses evolutionary particle-swarm optimization to evaluate power-system reliability. The results obtained are compared to Monte Carlo simulation and other population-based methods.	The work reported in this paper demonstrates that evolutionary particle-swarm optimization's variants can focus the search to the region of the state space where contributions to the formation of a reliability index may be found, preferable to conducting a blind sampling of the whole space.
Comparison of simulation methods for power system reliability indexes and their distributions	P. Jirutitijaroen; C. Singh	2008	38	How does one conduct reliability analysis of power systems using discrete the new Latin hypercube sampling technique?	Distributions of reliability indexes resulting from two sampling techniques are presented and analyzed along with those from Monte Carlo sampling. The distributions of indices are useful in risk analysis and certain stochastic optimization problems. The test system is a 12-area power system based on the data from an actual multiarea system.	This paper investigates Latin hypercube sampling in connection with power-system reliability evaluation, proposes a new sampling technique called discrete Latin hypercube, and compares distributions of reliability indexes resulting from the two sampling techniques with those from Monte Carlo sampling. The Latin-hypercube-based techniques are more effective

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
						than Monte Carlo for obtaining distributions of indices close to the real distributions.
A new approach to reliability evaluation of interconnected power systems including planned outages and frequency calculations	Z. Deng; C. Singh	1992	37	How does one evaluate reliability of interconnected power systems while including planned outages and frequency calculations?	Modeling and simulation: The paper simultaneously considers state space over all maintenance intervals and load states by using the concept of a reference load state and an equivalent composite-generation model and performs a decomposition-simulation procedure on this state space. This facilitates the development of a very fast algorithm and efficient storage.	The authors present an approach for reliability evaluation of interconnected power systems. In addition to the loss-of-load probability and expected unmet demand, the loss-of-load frequency can be computed efficiently. This approach can very efficiently include generating units' planned outages. Sample studies are presented to show that this algorithm is as accurate as the previous one but many times faster.
Power-system reliability in perspective	R. Billinton; R. N. Allan	1984	37	What are the philosophical aspects concerning power-system reliability?	This paper presents a literature review and discussion of quantitative reliability evaluation, data available, and data required to support such analysis.	This article discusses several philosophical aspects concerning power-system reliability, putting the reliability aspects in perspective and describing a hierarchical framework of analysis to discusses how the economics of reliability should be compared.
Power system reliability impact of energy storage integration with intelligent operation strategy	Y. Xu; C. Singh	2014	36	What is the impact of energy-storage integration on power-system reliability?	The authors perform a detailed case study and sensitivity analysis to demonstrate the effectiveness of the presented operation strategy and evaluation framework, and to provide valuable insights on the power-system-reliability	In this paper, the focus is on reliability improvement in the bulk-power system brought about by the use of energy storage in local distribution systems integrated with renewable-energy generation. The authors present an

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
					impact derived from the integrated energy storage.	intelligent operation strategy for energy storage that improves reliability considering the renewable-energy integration.
Generation/transmission power system reliability evaluation by Monte-Carlo simulation assuming a fuzzy load description	J. Tome Saraiva; V. Miranda; L. M. V. G. Pinto	1996	35	How does one evaluate Generation/transmission-power-system reliability by Monte-Carlo simulation assuming a fuzzy load description?	This methodology samples states according to the probabilistic models governing the lifecycle of system components and uses fuzzy concepts to model uncertainty related to future load behavior. This model can be used to evaluate generation/transmission-power-system reliability for long-term planning studies as one uses the more adequate uncertainty models for each type of data.	This paper presents a Monte-Carlo algorithm considering loads defined by fuzzy numbers, proposes new indices reflecting the integration of probabilistic models and fuzzy concepts, and discusses the application of variance reduction techniques where loads are defined by fuzzy numbers. A case study based on the IEEE 30 bus system illustrates this methodology. Each sampled state includes a fuzzy optimal power flow so that one builds its power on supplied membership function.
Static and dynamic aspects in bulk power system reliability evaluations	A. M. Rei; A. M. Leite da Silva; J. L. Jardim; J. C. O. Mello	2000	33	How does one evaluate bulk-power-system reliability considering both static (adequacy) and dynamic (security) consequences of disturbances that may occur in electric-power systems?	Modeling and simulation: The assessment of dynamic aspects requires the modeling of protection systems, control actions, and restoration processes. The cascading effects associated with dynamic problems are usually non-Markovian in nature, so they are better modeled through a Monte Carlo chronological or sequential simulation. The paper uses method combining time	This work extends the concepts and evaluation techniques for composite-generation and transmission-reliability assessment to provide performance measures considering both static (adequacy) and dynamic (security) consequences of disturbances that may occur in electric power systems. An extended IEEE-Reliability Test System, bearing in mind static and dynamic aspects, tests the

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
					simulation and transient energy function for the transient stability analysis.	proposed methodology. Loss-of-load probability measures adequacy and security. They are also decomposed to capture the contributions of various failure types considered: phase faults, etc.
Power system reliability enhancement using a thyristor controlled series capacitor	R. Billinton; M. Fotuhi-Firuzabad; S. O. Faried	1999	33	What is the impact of a thyristor-controlled series capacitor on power-system reliability?	Modeling and application: The paper presents a reliability model of a multimodule thyristor-controlled series capacitor incorporated in a transmission system.	This paper examines the impact of a thyristor-controlled series capacitor on power-system reliability. This application employs a thyristor-controlled series capacitor to adjust the natural power sharing of two different parallel transmission lines and, therefore, enable the maximum transmission capacity. The results of the investigations show a significant improvement in system reliability. The improvement is measured using two indices: loss-of-load expectation and loss-of-energy expectation.
Evaluation of power systems reliability by an artificial neural network	N. Amjady; M. Ehsan	1999	32	How does one evaluate power-system reliability with an artificial neural network?	The authors base this method on the artificial neural networks that require short training times.	The paper presents a new method for reliability analysis of power systems, which can solve difficulties of the previous reliability-analysis methods, such as low accuracy, complex modeling, and large computations. The proposed artificial neural network evaluates generating-unit and transmission-system reliability.

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
						Obtained results from this method for the IEEE reliability test system confirm the validity of the developed approach.
Impact of unified power flow controllers on power system reliability	R. Billinton; M. Fotuhi-Firuzabad; S. O. Faried; S. Aboreshaid	2000	31	What is the impact of unified-power flow controllers on power system reliability?	Analytical approach: Improvement is measured using three reliability-risk indices: the loss-of-load expectation, the loss-of-energy expectation, and system minutes. The paper also compares the effects of the unified-power flow controller and a thyristor-controlled series capacitor on the system reliability.	This paper examines the impact of a unified power flow controller on power-system reliability. The system employs the unified-power flow controller to adjust the natural power sharing of two different parallel transmission lines, facilitating use of the maximum transmission capacity. The results show a significant improvement in system reliability.
Reliability assessment of a restructured power system considering the reserve agreements	*P. Wang*; R. Billinton	2004	31	How does one evaluate the customer-load-point reliability in a deregulated power system considering customer choice?	Analytical approach: In this technique, an equivalent multistate-generation provider and an equivalent multistate reserve provider represent a generation company (genco), based on the market function of a genco. An equivalent multistate generation provider with reserve agreements, which has reserve agreements with other gencos, represents a genco. An equivalent multistate transmission provider with reserve agreement represents the transmission system between a genco and its customers, considering reserve agreements.	This paper presents a technique to evaluate the customer load point reliability in a deregulated power system considering customer choice on reliability. Reliability-network-equivalent techniques are extended and combined with the equivalent-assisting-unit approach to determine the reliability model of the equivalent multistate generation provider with reserve agreement. The paper also develops a procedure used to determine the reliability model of equivalent multistate transmission provider with reserve agreement. The IEEE reliability test system is used to illustrate

Table 4 Foundational papers in electric-power-supply reliability *(Continued)*

Document title	Authors	Year	Cite count	Research question	Research method	Research result
						the techniques.
Bibliography on the application of probability methods in power system reliability evaluation	R. Billinton	1972	31	What has been published on the application of probability techniques in the evaluation of power-system reliability up to 1972?	A literature review and a presentation of a bibliography of papers on the subject of the application of probability techniques in the evaluation of power-system reliability (up to year 1972)	This bibliography deals with the application of probability techniques in the evaluation of power-system reliability, but it does not contain all the material available on this subject. The many excellent publications clearly indicate the increasing use and interest in the application of probability methods in the evaluation of power-system reliability.
Unreliability cost assessment of an electric power system using reliability network equivalent approaches	P. Wang; R. Billinton; L. Goel	2002	31	How does one evaluate the customer-load-point unreliability cost caused by outages in different segments of the power system?	Analytical approach: This paper uses reliability-network-equivalent techniques to evaluate the customer-load-point unreliability-cost indices caused by outages in different segments of the power system. The percentage distribution of unreliability costs for system segments reveals the system's weak segments. A test system illustrates the application of these techniques.	Unreliability-cost evaluation of an entire power system provides a set of indices that can be used by a system planner to balance investments in different segments of the system and provide acceptable load-point reliability.
Impact of WAMS malfunction on power system reliability assessment	F. Aminifar; M. Fotuhi-Firuzabad; M. Shahidehpour; A. Safdarian	2012	31	What is the impact of situational awareness and controllability on power-system reliability assessment?	Modeling and simulation: The paper proposes a methodology to simulate a situation in which a limitation of either or both monitoring and control functions could spread the consequence of power-system events throughout the grid.	The monitoring and control infrastructure is assumed to be based on a wide-area measurement system. Monte Carlo simulation and a scenario reduction technique help overcome computational burdens on 9-bus and IEEE 57-bus systems.

Table 5 Research methods

Research method	Count anchor paper used the method	
	N	Percent
Modeling & simulation	16	41
Quantitative/Analytical approach	20	51
Literature review & discussion	3	8

Conclusion

This paper identifies the use of analytics to predict reliability issues and plan for grid reliability. To engender cutting-edge grid-reliability research activity, prospective authors in this space could examine topics such as:

- Modeling grid behavior,
- Detecting outages,
- Location analytics on smart-grid resiliency,
- Planning secondary and tertiary backup for the smart grid,
- Data management and pipeline to enable analytics,
- Internet of things (IOT) and sensors for analytics, and
- Recent advances in analytics and smart grids.

This systematic literature review of grid-reliability research provides a solid foundation to equip researchers with the most pertinent information, offers an enhanced EI research framework, and provides directions for future research in this domain.

Abbreviations

BPS: Bulk-power system; EI: Energy Informatics

Acknowledgements

The first author thanks her entire dissertation committee for their helpful advice.

Funding

This literature review is based on the first author's doctoral dissertation earned from Claremont Graduate University. No additional funding was used for this project.

Availability of data and materials

Additional supporting data is available from the first author.

Authors' contributions

The first author completed the literature review. The second author was the chair of the first author's dissertation committee, designed the paper structure, reviewed the findings, and proofread/edited the final paper. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

Received: 18 February 2019 Accepted: 12 April 2019
Published online: 02 May 2019

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