1. Introduction

In deregulated power system, large amount of power transactions forces the system to operate close to its design limits. This makes power system more vulnerable to potential failures thereby jeopardizing system reliability [1]. The system reliability is under constant threat from system contingencies, unpredictable load variations, operational issues, growing complexities of network, higher service level demanded by customers, etc., [2,3]. Hence, new methods and tools need to be devised to measure, monitor, and improve power system reliability. The newer technologies in data management, communication, and control methods together with emerging soft computing tools provide us powerful capabilities to improve system reliability.

The current literature survey deals with the new emerging areas of power system reliability. The paper is sub divided into nine different sub topics. The first topic deals with overview of power system reliability. This is followed by reliability assessment of generation, transmission and distribution systems, simulation/modeling for reliability assessment through soft computing techniques, economic
aspect of reliability evaluation and its enhancement using FACTS devices, reliability assessment of smart grid and also of hybrid/standalone renewable energy systems.

Following sections presents current status of researches in these important areas of power system reliability analysis.

2. Overview of Power System Reliability

This section deals with general introduction to power system reliability assessment. Reliability is the ability of a power network to return to a steady state condition from a sudden disturbance. The major parameters are voltage and frequency deviations. Other indicators are based on magnetic and kinetic assessment of power system [4]. The reliability of generation, transmission, and distribution systems need to be considered from planning stage itself [5,6]. In the literature, reliability assessment using probabilistic indices are suggested which are hierarchical in nature [7–18]. Reactive power plays a vital role in voltage instability and voltage collapse. A reliability assessment model has been developed by taking into account active and reactive power flow [19–22]. Different approaches for reliability improvements could be component redundancy, multiple power flow path, site testing, maintenance, and protection failure improvements [23–25]. A sequential Monte-Carlo simulation has been used for adequacy and security evaluation of power system [26–28]. A stochastic flow network modeling has been used for determination of co-related failures in transmission system [12,29]. A composite reliability evaluation of generation and transmission system has been carried out using capacity related cut sets [30,31]. Deterministic as well as probabilistic models have been formulated to assess reliability of composite system [32,33]. Mathematical formula has been developed for determination of reliability of n-feeder ring bus and triple bus distribution system [34,35].

3. Reliability Assessment of Generation and Transmission System

The reliability of entire power network is dependent upon reliability of generation and transmission system. For evaluation of generator reliability, various reliability indices are used. The papers in this section present reliability assessment using various indices in techniques such as Monte Carlo simulation, Neural Network, Game Theory etc.

The relationship between generator unit reliability and capital investment is used to determine system backup capacity [36,37]. Addition of renewable generation system introduces uncertain behavior in the power network. To estimate reliability of combined-conventional generation and renewable generation, the maximum power delivering transfer capacity of transmission system and various load points have been found using deliverable capacity probability table of multistate transmission providers [14,38]. For evaluation of generation reliability, various techniques such as Game Theory, Monte-Carlo Simulation, Neural Network, etc., have been used [39–45]. Reliability assessment of bilateral, pool, and hybrid market have been estimated through various techniques [46–50]. Demand side reliability assessment based on incentive, prices, etc., have been analyzed to lower undesirable effect of failures [41,51–54].

4. Reliability Assessment of Distribution System

The next important link in the chain after Generation and Transmission system is distribution system. The reliability of distribution system is evaluated considering various parameters such as cost of operation, supply interruption, mechanical failure rate, repaired time, load shedding, and load curtailment policies, etc.

General method of reliability evaluation consists of calculation of reliability indices for a given distribution network under different operating conditions [55–59]. This gives basic information about system reliability.

Reliability of distribution system having distributed generation is dependent on number of units, their location and capacity in each location. Reliability is assured through Bayesian network diagnostic interference method [60–62]. Reliability of such systems has also been evaluated through allocation of dispatchable distributed generator unit, considering cost of installation, operation, and interruption [63]. Another way of assessing reliability of distributed power generation is by considering load shedding and load curtailment policies [64]. Impact of conventional and renewable distributed generation on reliability of future distribution system can be evaluated by distributed generation adequacy, transition rate, mechanical failure rate and starting switching probability through Markov cut set algorithm [64,65].

Predictive reliability assessments of a distribution network have been done using historical outage data and mathematical models [1,66]. Average interruption duration has been taken as a measure of reliability [67,68]. In case of smart grid, reliability assessment of power system components, renewable generation, and communication infrastructure have been considered for reliability evaluation [69]. Evaluation of distribution system reliability is compared for three distribution systems viz. radial, ring, and flower using standard seven reliability indices. The result indicates that flower network exhibits better reliability [70,71].
Evaluation of distribution reliability of various customer sectors such as residential, small industrial, and commercial due to radial and sub transmission outages (considering component failures and weather) have been used to understand their impact on reliability of distribution configuration [72,73].

A new approach to reliability assessment of distribution network has been carried out by considering random repair time omission at load points for radial distribution system [74]. A study of reliability of general n-feeder ring bus system revealed that triple bus configuration has higher reliability [34]. Impact of station related failures on reliability of distribution network is found not to be significant [75].

Value based reliability planning is used to decide minimum reliability required from customer perspective [76]. Maintenance practices have been found to have profound influence over reliability of distribution network [72,77,78]. Reliability improvement of distributed generation system can be carried out by optimal feeder routing in distribution network [79,80]. Reliability of distribution network employing tele-controlled switches and microgrids by calculation of reliability indices have been evaluated [81,82]. Now-a-days large number of research is being undergoing in the field of modern or active distribution network where distributed generation (DG) is connected directly to the distribution network [33,83,84].

5. Reliability Assessment Through Simulation/Modeling

Those Simulation/Modeling is an integral part of reliability evaluation process. This section attempts to collate such various techniques used in the literature successfully.

Most of the papers surveyed use some simulation or modeling approach for determination of reliability indices of generation, transmission, and distribution systems under different parameter sets or operating conditions.

Monte-Carlo simulation technique has been used widely for determination of reliability of generating units [85–88]. This technique has also been used for reliability assessment of composite/bulk electric power system [44,88–101]. This technique has also been used for reliability evaluation of distribution system based on some operational parameter sets [27,67,74,102–105]. Markov Chain model is another technique which has been used for assessment of reliability of power systems [106–109]. Apart from Monte-Carlo simulation and Markov chain model techniques, Bayesian network technique have also been widely reported in literature [110–114]. Other methods reported in literature are graph theoretical approach [79,115], Taylor Series [116] and hybrid techniques [117–125]. For testing the reliability of protection systems in smart grid, a model checking approach is proposed [126].

6. Reliability Assessment through Soft Computing Techniques

For efficient and faster assessment of reliability of complex power networks with different constraints leads to higher level of computation complexity. Hence, newer tools based on soft computing techniques are being used. This section attempts to collate such techniques used for reliability evaluation.

Some popular computing techniques are reviewed here for reliability assessment of power system. Reliability assessment using fuzzy set has been used for determination of reliability performance metrics [18,127–142]. Similarly, Genetic algorithm [131,143–145], Artificial neural network [146], Firefly algorithm [147], Ant colony algorithm [148,149], Particle swarm optimization algorithm [90,148,150–152], Artificial immune system algorithm [148], Bacterial inspired evolutionary algorithm [153], Differential evaluation algorithm [154], Strength pareto evolutionary algorithm [155] have also been used in reliability assessment.

7. Economic Aspects of Reliability Evaluation

This section deals with reliability evaluation of economic aspects of power systems viz. interruption cost, power backup cost, investment cost of additional power component, replacement cost of aging equipment, etc.

Reliability evaluation of power system is also carried out based on some economic criteria such as interruption cost [84,156–167], backup capacity cost [36,42], cost of early warning system [168], risk of capacity deficit [101], investment cost of additional power component including addition of renewable generation system [80,168–173], replacement cost of aging transmission equipment [174], optimal maintenance cost [175,176], uncertain unit commitment cost [177].

8. Reliability Enhancement using Facts Devices

Flexible Alternating Current Transmission System (FACTS) devices are extensively used for power flow enhancement, voltage stability improvement, oscillation damping, etc. These are excellent devices for reliability enhancement as well. Hence, this section enumerates uses of various FACTS devices for reliability improvement.

Use of FACTS devices in transmission system shows overall improvement in system reliability [178]. The analysis was carried out using effective load duration curve
at demand point [179]. An indirect way of evaluation of system reliability is by use of FACTS devices for stability improvement [180].

Thyristor Controlled Series Compensator (TCSC) finds large application in reliability improvement of transmission system [181–183]. The assessment is based on calculation of reliability indices. Unified Power Flow Controller (UPFC) control setting and modes can be used to improve system reliability during post contingency condition. UPFC enhances system dynamic response through damping of rotor angle oscillations [184]. The system load carrying capacity risk is significantly reduced due to incorporation of UPFC [185,186]. Distributed Power Flow Controller (DPFC), a derivative of UPFC has also been used for reliability improvement at a relatively lower cost [184].

Inclusion of Interline Power Flow Controller (IPFC) improves system reliability calculated at load point and system levels [187].

Use of Static Series Voltage Regulator (SSVR) shows improvement in reliability of distribution system. However, the effect is dependent on capacity and location of SSVR [188].

Combination of FACTS devices such as TCSC and UPFC have shown significant improvement in reliability of system compared to other combination of FACTS devices [189,190]. The change in parameter setting of FACTS devices has shown significant impact on system reliability [191].

Reliability of Wind farm connected grid has been improved using Static Synchronous Compensator (STATCOM) due to efficient reactive power compensation [192–194]. Similarly, use of SVC shows improvement in reliability through improvement in power system adequacy [195].

9. Reliability Assessment of Smart Grid

Development of Smart Grid is taken place at faster speed all over the world. The reliability of smart grid can be enhanced by monitoring power system components, repair rates of components, improved communication infrastructure, robustness of cyber power networks etc.

9.1. Smart Grid

Reliability of smart grid can be improved by monitoring component reliability [126]. Reliability is estimated using multiple state Markov chain model incorporating failure and repair rates of power components. Reliability of smart distribution network can be evaluated using Pseudo-Sequential Monte Carlo simulation (PSMCS) incorporating reliability models of power system components and communication infrastructure. This method can be used to assess reliability of failure in a smart distribution network [69,196].

Smart grid uses digital communication system for data connectivity. The reliability of cyber-power networks in a smart grid can be assessed by an optimization model that maximized data connectivity in a cyber network with multiple data sources [197,198].

9.2. Micro Grid

Presence of Microgrid reduces failure rate and its duration and helps to improve reliability of distribution network. Due to isolated operation from upstream network there is significant improvement of reliability of internal as well as external customers. Adequacy calculation of conventional and renewable distributed generators in a microgrid can be estimated using stochastic models using load shedding and load curtailment techniques [64,81,199]. A probabilistic model of power system operation by predictive analysis of the microgrid reliability is also proposed [200].

9.3. Phasor Measurement Unit (PMU)

Due to non-availability of PMU statistics pertaining to field failure data and repair rate, reliability assessment of PMU system can be done with Fuzzy Monte Carlo simulation which uses statistics of extremes. A method to compute transient probability can be done using hidden Markov model. To improve data reliability in Wide Area Measurement system (WAMS), both the PMU data measurement and data transfer have to be reliable. To estimate reliability of failure of PMU and transmission branches, concept of observability reliability can be utilized. This is based on evaluation of loss of data expectation index. For overall evaluation of reliability of PMU, hierarchical Markov modeling is generally used [201–204]. Probability of failure of data transmission can be minimized by optimal placement of PMU and Phasor Data Concentrator (PDC) in a hierarchical structured WAMS [205]. Another method for reliability improvement of PMU placement can be done using Integer Linear Programming (ILP) Algorithm which tries to balance two conflicting objectives i.e. minimization of number of PMU’s and maximization of observable reliability [206,207].

9.4. Demand Response

Demand response helps to improve electricity service reliability without load shedding especially when operational limits are violated. Distribution system reliability and electricity prices are impacted by demand response and smart
metering in a microgrid. Higher price responsive demand side resources increases system reliability [208,209].

10. Reliability Assessment of Hybrid/Standalone Renewable Energy Systems

With fast depletion of fossil fuels, there is increasing use of renewable energy into the power system. The addition of renewable energy system greatly affects the system reliability due to variable nature of these power generation systems. Each type of renewable energy system has its own issues. Majority of power network depend upon solar, wind, or hybrid system. Hence, these sections have been dealt separately.

10.1. Solar

Reliability assessment of conventional power generation system with photovoltaic system is evaluated taking into account effect of hourly fluctuations on output of photovoltaic system. The algorithm can be used to determine loss of load expectations of the combined system [210].

Reliability assessment of independent grid connected Photo Voltaic (PV) system is carried out with respect to failure of components using fault tree method with an exponential probability distribution function [211,212]. Power system reliability performance can be improved with the addition of solar PV system. However, reliability improvement is significant if some energy storage system is carried along with PV solar cells [213,214]. Reliability of solar PV system can be improved by optimizing power production through its operation at its maximum power point [215].

10.2. Wind

Reliability assessment of wind power generation can be done by predicting wind speed through a time series model using Auto-Regressive Moving Average (ARMA) or Monte-Carlo simulation. This allows the reliability assessment of wind power generation system. The method helps to predict the reliability of wind power system [163,216–223].

Quantum of wind penetration level can be decided based on reliability assessment by obtaining probabilistic quantitative indices which take into account load operation [148,157,224,225].

In the literature, reliability assessment of power electronic converters for wind energy conversion system takes into account component reliability of converters with temperature as stress factor. It also considers semiconductor power losses based on switching and conduction losses. This can help to identify least reliable component in any converter [226]. Reliability of wind power generators can be determined by deciding on type and number of wind turbine generators, including capital maintenance, operating cost, and consumer interruption cost. Significant economic and reliability benefits can be obtained by choosing appropriate combination of number and type of wind generators at different sites [169]. Another approach of estimating reliability of wind energy integration can be carried out by considering wind speed, wind variability, generation facility, turbine forced outage, and available transmission capacity [38,227–230].

10.3. Hybrid

Reliability of power system grid can be improved by incorporating hybrid system composed of Photovoltaic module, Proton exchange membrane fuel cells and Hydrogen storage tank.

Reliability of small power system can be improved using hybrid system consisting of solar energy and small hydro. Solar power as a single source has a reliability lesser than 50% but the same can be improved by adding storage capacity, such as small hydro. A combination of solar power with small hydro is desirable for higher reliability than isolated solar power source [170,231,232].

Generation adequacy reliability evaluation of hybrid hydro and wind farm incorporating time series wind speed model have been carried out. The overall model combines quantitative assessment of six configurations with different wind farm capacities. Water reservoir volumes and water inflow is also used to predict the reliability of the hybrid system. Result indicates that system adequacy decreases when hybrid combination takes inadequate reservoir capacities and water inflows [233]. A composite system comprising wind and solar PV generation which incorporates multiple correlations amongst wind speeds, insolation, bus/regional load curves have also been tried to evaluate composite generation and transmission system reliability. Result indicates that accurate model of multiple correlations increases the reliability evaluation of the composite system [234]. Another probabilistic model of composite wind generation and hydrogen storage system have been investigated to determine amount of secondary/tertiary generating reserve required to maintain a certain level of reliability [235].

Reliability evaluation of composite solar PV and pump storage power plant can be used to improve power supply reliability by devising optimal pump storage power plant operation pattern [236].
11. Reliability Assessment in Deregulated Power Systems

Power systems reliability assessment and enhancement is being influenced by the deregulated energy market, as competitive electricity market influences system reliability. This section deals with the assessment of reliability in deregulated or restructured power system.

An analytical probabilistic model for reliability evaluation of the energy market and a methodology for incorporating the market reliability studies by Markov modeling based on market performance indices is proposed [37, 237]. Monte Carlo simulation is also used in deregulated power system for reliability evaluation [44, 238–240]. Due to large number of bilateral transactions in deregulated power systems, and resulting line outages, reliability of the system is reduced. This reliability is also being decremented by removing the redundancy in order to achieve minimum energy cost. As the minimum cost is the basic criterion for Independent power producers (IPPs) in deregulated power system, high standard of power system reliability can’t be maintained [241]. There is also a need to determine transmission reliability margin in deregulated power system which ensures the transmission system for reasonable range of uncertainty in operating conditions of the power system [242]. Concept of demand side management (DSM) is present in deregulated power system and it has improved the nodal as well as overall reliability of the system [54, 243, 244]. Another concept of demand-price elasticity also emerged with the deregulation, where price of electricity interacts mutually with load. The demand price elasticity improves the system reliability along with reduction in volatility of nodal spot price [245, 246]. Power flow tracing which was previously used for transmission pricing in competitive market is proposed for reliability evaluation in deregulated power system [247].

12. APS in Current Research

Based on papers reviewed, following areas require further focus to fill gaps in current research. Some of the areas suggested for further exploration are listed below:

- A Markov model for repairable multi-state system with fuzzy Bayesian interval estimator for fuzzy system reliability evaluation could be considered for further exploration.
- A further extension of multi-level redundancy allocation problem could be by considering a complex configuration or difficult level of case design so as to closely mimic real world system.
- Artificial neural network-based systems could use better training samples to improve accuracy of the performance.
- Accuracy of models employing particle swarm optimization for reliability estimation of maintenance scheduling process could be further improved by tailoring the reliability estimation to behavior of specific user or roles.
- A more comprehensive analysis of different systems and networks could be carried out by considering other meta-heuristics such as Artificial Immune System (AIS), Differential Evaluation (DE), Gravitational Search Algorithm (GSA), Tabu Search (TS), Firefly Algorithm (FFA), Bacteria Foraging Algorithm (BFA) etc.
- In the area of assessment of maintenance failure rate and repair time reliability assessment could focus on reliability of power system components based on aging, uncertainty in power generation system, etc.
- Reliability assessment of type of maintenance appropriate for components of large scale solar photovoltaic systems could be explored.
- Reliability assessment of renewable energy systems such as solar and wind could be explored by incorporating meteorological model taking into account movement of cloud patterns, wind flow patterns, etc.
- Monte-Carlo simulation methodology could be used to investigate optimum failure rate and repair time for distribution components considering associated costs. These indices could serve as benchmark for power distribution companies.
- Reliability assessment of customer weighted failure frequencies and downtimes together with system average failure frequencies and downtimes could incorporate more variables so that the accuracy of prediction model could be improved further.
- Optimal placement of distributed generation for time varying loads incorporate switching operations, protection system failures in the event of faults.
- Evaluation of reliability of PMU with fuzzy Monte-Carlo technique could be used to improve accuracy of results.
- Evaluation of reliability of PMU for transient probability (for better observability of whole system) could be done using HMM.
- Reliability evaluation of systems using digital relays having annunciation and corrective measures can be carried out for improvement of wide area system reliability.
- Probabilistic reliability assessment of power system operation could combine fuzzy set theory and probability methods to deal with both randomness and fuzziness in time varying and/or condition dependent data modeling.
Based on the papers reviewed, gaps in research are also indicated in this paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Table 1. Numbers and year of publication of surveyed papers.

| Category                                      | Number of papers | Year (From–To) |
|-----------------------------------------------|------------------|----------------|
| Overview of power systems reliability        | 33               | 1995–2017      |
| Reliability assessment of generation and transmission system | 20               | 2004–2016      |
| Reliability assessment of distribution system | 33               | 1996–2017      |
| Reliability assessment through simulation/Modeling | 47               | 1997–2016      |
| Reliability assessment through soft computing techniques | 32               | 1999–2016      |
| Economic aspects of reliability evaluation   | 27               | 1996–2017      |
| Reliability enhancement using FACTS devices  | 18               | 1999–2016      |
| Reliability assessment of smart grid         | 18               | 2009–2017      |
| Reliability assessment of hybrid/Standalone renewable energy system | 33               | 1995–2016      |
| Reliability assessment in deregulated power system | 12               | 1998–2015      |

13. Conclusion

This paper is a bibliographical survey of 247 publications covering the period 1995–2017 (up to first 5 months). The survey is subdivided into ten different topics with each topic describing the overview of related literature more precisely in Table 1. The information collated here covering past 22 years will be of immense help to researchers working in the field of power system reliability, practicing engineers, postgraduate, and doctoral level students.

- New models for optimal power system operation planning could incorporate variables, such as protective device location, switching of these devices, future growth scenarios, and risk analysis to build robust reliability model.
- Estimation of future load growth in power system could be applied to multimode systems instead of single node systems.
- Further investigation is needed to study the effect of maintenance on repair in predefined time based maintenance oriented systems to understand the impact of maintenance on component failure.
- Impact of large scale deployment of energy storage devices in renewable energy systems could be studied for reliability evaluation. This could help in planning of energy storage and renewable energy source integration, expansion, economic feasibility analysis, etc.
- Reliability assessment of maintenance system could be studied involving human failure, partial failure, and catastrophic failure.
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