A Review on Power System Reliability with Advanced Power Quality Techniques

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Abstract: A power system is highly susceptible to system irregularities such as control failure, security system failure, instabilities, and inadvertent human errors. Ensuring the reliability of the power system is vital for assuring the quality of the power supply by taking definite steps to safeguard against probable events that involve an element of risk.. This comprehensive review presents the significance of reliability, reliability indices, various reliability methodologies, and supporting literature.

1. Intorduction

By definition in dictionaries, *reliable* refers to something or someone that is capable to be trusted or believed because they work and/or behave well in the direction we expect. Synonyms for reliability are trustworthiness, accuracy, and loyalty.

The feature of reliability is quite important pillar in each segment of any society. In “Economics of Reliability Engineering,” Aggarwal (1993) emphasizes “for a producer, reliability is a matter of remaining in the business so that business volume and profit will be substantially increased once his reliability reputation is established.” Therefore, a reliable system has the ability to consistently perform assigned function. Generally, reliability of all activities and services is higher in the industrialized and developed than in emerging societies.

The reliability of power system is reflected in a reliable generation of sufficient energy and its transmission and distribution to end users. It is about ability to provide an adequate delivery of electrical energy encountering the operating conditions. Moreover, a desired performance on reliability is to respond quickly enough to unexpected failure situation.

Energy generation and supply is experiencing a great transformation in the ongoing century and will cease to exist as we know it. Modern energy sector is driven by carbon-free energy, decentralized energy systems, and inclusion of information technologies, facing always arising challenge – reliability of energy supply. Therefore, in front of the evolving power sector, there is a difficult task – to provide and maintain reliable power around the clock while reducing the greenhouse gas emissions and meeting the growing energy demands of the global population at the same time.

2. Motivation

Reliable energy systems can drive progress in societies across all segments, and vice versa blackouts can cause severe losses. Several decades ago when electrification was poor in most of the world, electricity was a kind of luxury, even though blackouts were more frequent. Today, functioning of the modern society is utterly reliant on electricity, so outages can impact the society in the range of short inconveniences to very serious damage.

In the case of longer blackouts, widespread disruptions leading to the overall instability occur − interruptions in traffic, medical systems, water supply and sewer system, payment transactions and business interruptions, sudden growth of crime, and arising vulnerability of the security system.

Therefore, resilience of the electricity grid needs to be continuously strengthened and reviewed which increase its reliability at the same time. Resilience response of the power system due to disturbances is the ability of a system to absorb a shock without collapsing, to recover from a shock, to adapt through self-organization and learning and eventually self-transformation (Heinimann 2014), so that preparedness for future vulnerabilities is one of the essential tasks of grid operators. In the pre-event planning besides creating the possible scenarios and prognoses, Haseltine and El-Sheikh Eman (2017) suggest using a neural network to conduct “pre-event” analysis of a power grid to determine if it is susceptible to a failure. To ensure resilience and improve reliability of power supply, European Union (EU) obliges its member states to develop a national risk assessment and a risk preparedness plan in the power supply sector. Stable electricity grids are indispensable to the normal functioning of modern cities and critical for preparedness, response, recovery, and mitigation in the emergence management (Chang and Wu 2011).

To maintain the reliable energy system, it is essential to provide sufficient and flexible energy sources. It is equally important to maintain steady frequency as well as voltage at different levels in different parts of the power system (generation, transmission, distribution, consumption). Frequency is defined by how fast generators spin (U.S. Department of Energy 2016), and voltage is the force driving the flow of electricity, which is caused by the difference in electrical charge between two points (Bradley MJ & Associates 2017). The standard power frequency in different countries in the world is 50 Hz (for example, in the United Kingdom and Russia) and 60 Hz (in the United States and Brazil).

Billinton and Allan (1994) explain that power system reliability assessment can be divided into two basic aspects: system adequacy and system security, where adequacy is defined as the existence of sufficient facilities within the system to satisfy the consumer load demand and system operational constraints, while security is described as the ability of the system to respond to disturbances arising within the system. The authors make difference between adequacy that is associated with static conditions and security that is, therefore, associated with the response of the system to whatever perturbations.

North American Electric Reliability Corporation (NERC 2019) defines the bulk power system reliability as a function of adequacy and operating reliability, where adequacy is defined as “the ability of the electric system to supply the aggregate electric power and energy requirements of the electricity customers at all times while taking into account scheduled and reasonably expected unscheduled outages of system components,” while operating reliability is defined as “the ability of the electric system to withstand sudden disturbances to system stability or unanticipated loss of system components.”

Australian Energy Market Commission defines a power system as reliable when there is enough generation, demand response, and network capacity to supply customers with the energy that they demand with a very high degree of confidence. This implies meeting the reliability standard which requires at least 99.998% ofthe forecasted customer demand to be met each year. The contemporary challenge is achieving 99.999% supply reliability around a clock.

The reliability of the bulk power system is one of the greatest responsibilities of grid operators. In order to deliver resilient, reliable, flexible, secure, sustainable, and affordable electricity, there is a need for modernization of power grids. In this respect, the U.S. Department of Energy established the Grid Modernization Initiative (GMI) with the aim of developing the concepts, tools, and technologies needed to measure, analyze, predict, protect, and control electricity grid of the future.

Given that the main constraints in providing electricity around a clock is an immature or aging grid, an increased investment is required to upgrade reliability for everyday operations, so the main question posed in reliability economics is “where or on what should the next dollar be invested in the system to achieve the maximum reliability benefit?” (Billinton and Allan 1992). Other reasons for outages can be cyberattacks, human errors, inadequate equipment maintenance, tripping, and overloading of transmission lines (Haes Alhelou et al. 2019). The increased digitization of power systems means also the increased cyber vulnerability.

3. Failure Examples of Reliable Power Supply Worldwide

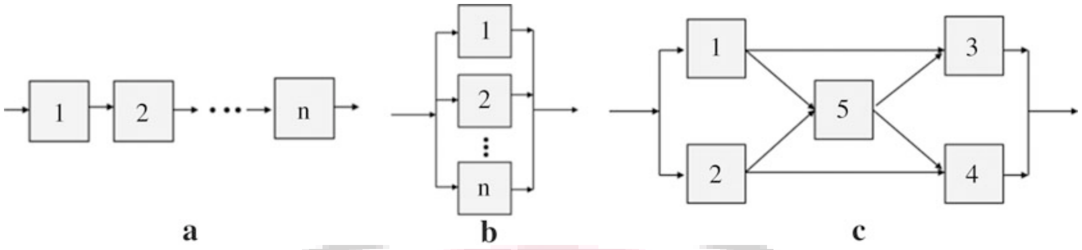
The report of International Energy Agency et al. (IEA et al. 2019) revealed that six countries – Eritrea, Eswatini, Honduras, Maldives, Palau, and South Sudan – have more than three disruptions or aggregate disruption of more than 2 h per week indicating unreliable power delivery. It is expected that world’s poorest countries suffer also from the low reliability performance of the electricity supply; so in these societies, the higher frequency of blackouts and brownouts indicate the higher level of vulnerability of the power grid. A lack of access to reliable and sustainable energy in sub-Saharan countries is also described in the Afrobarometar survey (2019), which found out that fewer than half (43%) of people in 34 African countries report a reliable supply of electricity. This percentage is the highest in Mauritius (98%) and Morocco (91%) and the lowest in Malawi (5%) and Guinea (7%). Ghana stands out since the share of citizens enjoying the reliable power is more than doubled, from 37% in 2014 to 79% in 2018.

However, it is a real challenge to provide a continuous and uninterrupted supply of the right quantity and quality of electricity 24/7/365 even in developed and modern countries. The U.S. Energy Information Administration (2019) reveals that customers in the United States experienced an average of the 1.3 interruptions and were without power for 4 h in 2016; when excluding natural hazard events, customers in this country experienced one outage lasting almost 2 h in this year. One of the world’s leading cities, New York City, faced several large blackouts in 1965 and 1977 and several blackouts in the 1990s, 2003, 2006, 2011, 2018, and the last one in July 2019 lasting for ca 4 h causing real trouble to the residents. One of the latest nationwide blackouts took place in Venezuela for 5 days in March 2019, following the political and economic crisis and having severe consequences including deaths. People of Argentina, Paraguay, and Uruguay experienced also the nationwide power blackout in June 2019 that lasted ca 12 h and affected 50 million people.

Though social and working needs of people in modern world demand the power supply working constantly, outages due to random failures that are generally out of control of the supply system (for example, due to extreme weather conditions – hurricanes, floods, or earthquakes) occur. For instance, Hokkaido earthquake in Japan in September 2018 left the entire island in the dark for 2 days, but restoring full electricity on island took more than 7 days. In February 2014, a severe icing caused blackout for 10 days in Slovenia.

4. Reliability Evaluation Techniques

The qualitative and quantitative reliability assessment techniques for power systems have been developed for decades. In the assessment of system reliability, the mathematical and graphical models are used. AlMuhaini (2017) states that the reliability assessment should consist of two parts: modeling of the reliability characteristics of the components (generators, transformers, and batteries) and calculation of the reliability of the power system, where it is a usual practice to assume that the failures are independents in modeling the component reliability data (Fig. 1). One of the most popular reliability evaluation methods is reliability block diagram (RBD) and fault tree analysis (FTA). As defined in work of de Vasconcelos et al. 2019, the reliability block diagram is a graph of system components connected according to their logical relation of reliability (where each component is represented by a box that is assumed to be in operating or failed states), enabling the analysis of the effect of component failures on different system configurations, while



Challenges of Reliable Power Supply with Emphasis on Renewables, Fig. 1 Reliability block diagrams for series (a), parallel (b), and “bridge” (c) systems. (Source: Vasconcelos et al. 2019)

the fault tree analysis shows the failure process and possible combinations of components that can cause a system failure.

The reliability of power supply systems is usually evaluated by a combination of two indexes describing how often and how long electrical blackouts last – the system average interruption frequency index (SAIFI) and the system average interruption duration index (SAIDI). The average service unavailability index (ASUI) is also used as a ratio of SAIDI and number of hours a year. Security or customer interruptions (CIs, similar in concept to SAIFI) and availability or customer minutes lost (CMLs, similar in concept to SAIDI) are used in Ireland and Great Britain. Also used reliability indicator is the average service availability index (ASAI) which is a ratio of customer hours of electricity availability and customer hours of electricity demand. NERC also uses the severity risk index (SRI) that is calculated to measure the relative severity ranking of daily conditions based on performance rates and their impact on the bulk power system, giving a broader picture of year-on-year trends of the relative conditions.

5. Reliability of Renewable Energy

In boosting reliability of electricity grid, it is also of high importance to prioritize energy-efficient practices and clean energy technologies. Notable progress has been made on improving the reliability of renewable energy in recent years. Private power industries have joined with the public sectors to cope up with the power demand and improvement of the reliability of renewable electricity supply.

Renewables has experienced a great expansion over the past decade that exceeded all expectations – international financing commitments for clean and renewable energy in developing countries amounted 9.9 billion dollars in 2010 and rose to 18.6 billion dollars in 2016, a tenfold increase from the early 2000s (United Nations 2019). They play a noticeable role, since they can cover a significant portion of the global energy demand. Renewable energy has an additional opportunity to grow in time of shutting down nuclear, coal, or gas power plants. According to the projections of the Bloomberg New Energy Finance (2019), wind and solar will make up almost 50% of the world electricity in 2050 – “50 by 50.”

Albeit notable progress over the past decade, use of renewables still face financial, regulatory, and technological obstacles (Petrović 2020). In meeting challenges consisting in the Sustainable Development Goal 7.1, a considerable growth of renewable energy must be ensured so that governmental policies need to provide a larger inclusion of renewables into the energy sector. Furthermore, the Intergovernmental Panel on Climate Change asks for renewables share of 70–85% by 2050 to avoid experiencing of the worst impacts of climate change. Zuijlen et al. (2019) in their research found small changes of 6% in the total generation from intermittent renewable energy sources between favorable and unfavorable weather years, while emissions differ up to 70 MtCO2 yr. – 1 in developed model of the 2050 Western Europe power system. Energy professionals and advocates of renewable energy claim that the growth of power supply from wind and solar energy can be manifold while reliability would not be affected and air pollution would be significantly in decline.

Zappa et al. (2019) in their research found that a 100% renewable European power system projected in 2050 could operate with the same level of adequacy as today. Budischak et al. (2013) modelled over 28 billion combinations (each tested for 4 years of load and weather data) of renewables – inland and offshore wind and photovoltaics with storages such as batteries and fuel cells, for a large regional grid system (72 GW) – PJM Interconnection in the eastern United States. Finally, the authors claim that this electric system can be powered 90−99.9% of the time by renewables, if it is based on the optimal mix of generation and storage technologies that they found – 17 GW of solar, 68 GW of offshore wind, and 115 GW of inland wind with a hydrogen storage system.

6. Distributed Energy Supply

As a support to the development of the renewable and reliable energy future, there is a concept of distributed generation (DG). Deployment of the distributed energy technologies such as photovoltaic (PV) panels or wind farms closer to the end users as a support to the macro grid can remarkably upgrade the reliability and continuity of power supply in stress situations. Though DG has many advantages, it fluctuates randomly; so, a higher penetration of DG without power electronics may jeopardize the grid stability (Fusheng et al. 2016). Considering the problem of controlling the generated power and voltage output from renewable energy, power converters and inverters play significant role in the integration of renewables into the grid, given that it is essential to provide a proper voltage at the point of connection of renewable energy generator to the grid.

In developing distributed energy supply system, mathematical optimization models are widely used. While in designing the optimization model, it is usually assumed that all components are available at any time, Hollermann et al. (2019) respond to the challenge of guaranteed energy supply during the failure of 1 component and create n-1 reliable model of energy systems. However, a cascading effect of the failure in one part can occur in another part of the power system. Due to the operational dependencies between nodes, the failure of a few key nodes can cause a large cascade of failures resulting in the breakdown of the power system; so, it is crucial to study the vulnerability of the power system in conditions of the cascading failures especially in terms of evaluation of the importance of nodes in the network and their cascading potential (Seo et al. 2015).

Off-grid or stand-alone energy systems are the smart solutions in meeting the electricity needs of homes or smaller communities and businesses independently, mostly in developing countries where the main grid is either not developed or it is uneconomical to extend it due to remoteness of the location (Chmiel and Bhattacharyya 2015). There is an array of examples where setting the off-grids brought the electricity into hard-to-reach settlements and made power delivery even more reliable.

The Scottish island Eigg is an example that it is possible to meet residents' energy needs in small and isolated communities with no access to a national grid, by using energy of renewables. The Eigg residents, never connected to the mainland electricity grid, lacked earlier regular access and were dependent on diesel and noisy generators. Today, 38 households and 5 business units on Eigg island are ca 95% supplied by the electricity generated from the water, wind, and solar energy using back-up batteries to store excess power generated by renewables, representing an energy self-sufficient community (Chmiel and Bhattacharyya 2015). In the case the nature does not cooperate, they start generators to supplement the power generation.

In the report of International Energy Agency RETD (2012), several case studies of remote areas are described as examples of how renewable energy technologies can significantly boost the reliability of power supply. Floreana (the smallest island of the Galapagos Archipelago in the East Pacific, Ecuador) used the electricity generated by a diesel gen-set working only 13 h per day in the only village of the island, while the households outside the village had no access. A great shift happened in 2003 by the implementation of the PV/Diesel hybrid project – a multiuser solar hybrid grid (MSG) and 5 individual photovoltaic facilities for the farmhouses outside the main village were installed and the service quality was single phase AC, 24/7 to all users. In 2011, the facility was updated to substitute Jatropha biodiesel for the remaining diesel generation.

Another example described in the IEA RETD report (2012) is Ross Island (Antarctica), a host of two remote research stations – Scott Base (owned and operated by the Antarctica New Zealand – AntNZ) and McMurdo Station (owned and operated by the U.S. National Science Foundation – NSF), where energy needs are exclusively related to the research as the only local economic activity and ca 1200 researchers working 3–4 months a year. Phase 1 of the project with the aim to displace up to 50% of the diesel production was implemented by installation of three wind turbines and flywheel storage system. In later phases, more than 20 wind turbines may be installed and solar power is also considered given that most researchers stay on island in the summer months with 24-hour sun.

7. Solutions in Improving Reliability

Hybrid Renewable Energy Systems:
Wind and sun power are considered as the abundant and free energy sources, but depending on meteorological conditions. However, researchers found alternative solutions to make up this drawback of the renewables. It seems that a solution is the hybrid renewable energy system (HRES) that combines two or more renewable energy sources or renewable source(s) with conventional source, which can be either on-grid or stand-alone. In designing the HRES, accuracy of load assessment and sizing methodologies are of high importance. Though they show higher level of reliability than a system relying on a single energy source, there is a need for the optimization of HRES in terms of fuel flexibility, efficiency, reliability, emissions, and economics (Amer et al. 2013; Pranav et al. 2017). Amusat et al. (2016) faced the variability challenge which is inherent in the design of renewables – dependent integrated energy systems for heat and power supply, where a superstructure contains two generation and three storage alternatives. The authors developed model equations for the components of the energy system, considering two objectives – cost minimization and reliability maximization. They found a solution in a multiobjective genetic algorithm to obtain a Pareto-optimal set of designs which trade-off between both objectives in the model.

As an example, Tajeddin and Roohi (2019) designed a disruption-proof wind farm through hybridization with biomass energy in the case study at a site in Isfahan, Iran, with the following methods used: meteorological data analysis, evaluation of biomass resources, and feasibility analysis through an economic assessment concerning the hybrid systems.

Bertsiou et al. (2018) designed hybrid renewable energy system for the electricity generation and covering the drinking and agricultural water demands through the desalination of sea water in Fournoi island (eastern Aegean Sea), consisting of four wind turbines, a desalination plant, a small hydroelectric station, a pumping station, and two water reservoirs. In this case, the analysis of the 10-year reliability is done showing that HRES has dominant role on the coverage of electricity needs in one-third of the year (May to July and November) and there are months (September and October) of energy independency.

Kavadias (2010) emphasizes that the standalone wind hybrid systems using energy storages are becoming a viable and reliable solution for the building sector, which in the national energy consumption reaches up to 40%.

7.1 Energy Storages

The power grid is a complex system where the electricity supply and the demand need to be balanced at any given time. Energy storages are that crucial component that makes the low-carbon electricity system more reliable, since they have a task to store the excess electricity that will be used later when needed. In this point, energy storages reduce the grid congestion and provide energy reserves when there is a lack of energy generation. There are many methods to store energy and Energy Storage Association (ESA) uses five types of storage technologies: batteries, thermal storages, mechanical storages, hydrogen, and hydropower storages. Though hydropower reservoirs fitted with pumped storage technologies are the most common type of energy storage, the battery technology is experiencing development and a fast growth.

Batteries can be lithium-ion (Li-ion), lead-acid battery, sodium sulfur (NaS), nickel−cadmium (Ni-Cd), electrochemical capacitors (ECs) and flow batteries. However, batteries are better suited for the small-scale systems ranging from watches and computers to building backup systems, while the pumped hydropower storage, on the other hand, stores huge amounts of energy and can be found only in large power systems (Novaković and Nasiri 2016). Thermal storage technology enables storing the excess thermal energy to be used later for cooling and heating applications, while mechanical storages use kinetic or gravitational energy. Excess electricity can be also transformed into hydrogen and stored as a compressed gas, a solid, or a liquid. There is a need for the data-driven optimization approach in the selection of the best suited energy storage as a decision-support tool for the decision-makers (Li and Wang 2018).

European Commission (2017) estimated that the global installed capacity of electricity storage in 2014 was 171 GW3, ca 2% of total generation capacities. As ESA reports (2019), the U.S. energy storage market nearly doubled in 2018 (23 GW of total energy storage installed) due to significant decreases in pricing, technological developments, and needs for improving infrastructure reliability, which brought a historic exponential growth for implementation of energy storages in grids, so further expansion is also expected.

7.2 Smart Grids

Existing energy system must be modernized to maintain or to become reliable in circumstances of the constantly growing energy demand. In many developed countries, there is an aim to renew their electrical grids from generation to transmission and distribution which requires significant governmental investments and technological developments for the purpose of tailoring smart grids.

Modern concept of "smart grids" is a cornerstone of the "smart cities" and implies the digital and other innovative technologies for intelligent monitoring and managing the electricity delivery system from generators to end users in homes and businesses, with final aim to optimize the system reliability and resilience and reduce the costs and environmental impacts. In the context of modern energy sector and sustainable communities, smart grids promote the electricity generated by renewables, boost the energy efficiency, replacing the traditional concept of electrical networks.

World Economic Forum (2017) gives a positive example of smart grid – the Florida Power and Light used the grid data to monitor the status of grid and operations and in this way contributed to 30 million dollars in the operational savings in 2014. One of good and first examples of smart grids and smart meters in Europe are implemented in Norway (e.g., Aust-Agdre and Vest-Agder) and Italy (e.g., Milan, Genoa and Padua). Given that India suffers from the greatest energy loss in the world, implementation of the smart grid solutions would totally change its energy reality.

7.3 Super Grids

The super grids or mega grids are seen as the networks of energy grids of several neighboring countries that enable sharing the electricity between them and, in this way, strengthening the reliability of power supply. They are especially supportive to the renewables – in the case of sun shining and wind blowing in one area and not in another or in the case of harvesting remote renewables off-shore or in the desert.

In this direction, the EU is developing regional or supranational platforms. The Great Britain makes efforts in the interconnectivity of the European countries by constructing the underwater connections to the energy grids of Ireland, France, Belgium, and Denmark.

Under the European Energy Programme for Recovery, the Santa Llogaia-Baixàs power line is developed to connect the power system of the Iberian Peninsula to other European energy markets and to double the existing electricity interchange capacity between France and Spain, from 1400 MW to 2800 MW.

There is also a project called Asian super grid, a scheme of energy interconnection between Japan, Russia, North Korea, China, and Mongolia. In ensuring reliable power supply in the USA, broader regional market coordination is also needed. For instance, on a day that is sunny in Arizona and wind is missing in Wyoming, surplus of solar power in Arizona can compensate for less wind energy in Wyoming (Bradley & Associates 2017).

8. Future Directions

As defined in the Sustainable Development Goal, governmental policies worldwide need to ensure universal access to affordable, reliable, and modern energy services by 2030. Even when electrification in remote rural regions is completed, the next challenging task is to maintain the energy services reliable. Evolving energy sector, also driven by a transition in the generation resources, is supposed to ensure reliable power supply along with increasing the share of renewables and using the environment friendly technologies. The inclusion of renewable energy sources promotes energy diversification which boosts reliability and security of the power system.

Each country should design a blend of energy sources in order to be protected from the dependence on a single energy sources or provider and to develop reliable power generation. In high income countries, grid operators make efforts to provide the growth of renewables using a plenty of tools and practices to accommodate them into the power systems.

Power outages can be pretty costly so that investments in improving the reliability are needed. It is mandatory in a secure energy system of any country to make adjustments to the power supply continuously, to be able to respond to both the daily patterns of human activity and problems arising from a system overload or an event of natural hazards. The U.S. Department of Energy is also funding a research into using artificial intelligence for the sake of predictability of potential blackouts and locating the anomalies as well as finding solutions to keep power delivery constant in the case of a failure.

Using synergy of new technologies and smart grids, modern energy companies offer to their customers the energy products and services relying only on renewables, presenting the option of social responsibility and environmental awareness. Consumer “inside the fence” decisions such as rooftop solar and behind-the-meter batteries at the household level help shape an increasingly decentralized grid in the world.

The number of wind and solar plants grows, while the number of coal plants drops. In future, there is going to be an opposite situation to the current – fossil fuels should become a supplement to the renewable power generators in electricity grids when renewables are not able to meet demand. Given that a single renewable generator can provide fluctuating electricity, there is a need to combine diverse renewables at diverse sites using next generation storages to ensure the reliable renewable energy generation and supply.

Cross-References

▶ Energy Investments
▶ Energy Potential
▶ Energy Supply
▶ Energy Technology
▶ Fuels
▶ Renewable Energy
▶ Resilience

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