

Review

# A Survey on Power System Blackout and Cascading Events: Research Motivations and Challenges

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**Abstract:** Power systems are the most complex systems and have great importance in modern life. They have direct impacts on the modernization, economic, political and social aspects. To operate such systems in a stable mode, several control and protection techniques are required. However, modern systems are equipped with several protection schemes with the aim of avoiding the unpredicted events and power outages, power systems are still encountering emergency and mal-operation situations. The most severe emergencies put the whole or at least a part of the system in danger. If the emergency is not well managed, the power system is likely to have cascading failures that might lead to a blackout. Due to the consequences, many countries around the world have research and expert teams who work to avoid blackouts on their systems. In this paper, a comprehensive review on the major blackouts and cascading events that have occurred in the last decade are introduced. A particular focus is given on the US power system outages and their causes since it is one of the leading power producers in the world and it is also due to the ready availability of data for the past events. The paper also highlights the root causes of different blackouts around the globe. Furthermore, blackout and cascading analysis methods and the consequences of blackouts are surveyed. Moreover, the challenges in the existing protective schemes and research gaps in the topic of power system blackout and cascading events are marked out. Research directions and issues to be considered in future power system blackout studies are also proposed.

**Keywords:** energy system security; power system emergency; power system blackout; power system cascading events; emergency management; power system stability; smart grids; frequency protection; power system protection; power outages

## 1. Introduction

### 1.1. An Overview and Motivations

The ability of power systems to maintain stability and to ensure continuous supply of electrical power to customers in the event of a disturbance is of critical importance [1–3]. As the power system is spread over large geographic regions, the probability of facing different types of faults and failures is high [4]. Unfortunately, unpredictable faults and cascading events usually lead to a blackout which might affect modern life.

As the demand for energy grows, modern power systems are operated close to steady state stability, which can easily lead to a critical situation [5–9]. Therefore, modern power systems

must be equipped with suitable control and protection schemes in order to cope with disturbances. The ability of a power system to maintain steady state and transient stability is the subject of decades of research [10,11]. In power systems, frequency, voltage and rotor angle of synchronous generating units are the most important quantities that should be properly controlled in order to maintain the power system stability [5]. Power imbalance between demand and generation directly affect the frequency stability, while the voltage is directly affected by the reactive power imbalance [12–15]. The rotor angle behavior is also a representative of the stability and synchronism in the whole power system. If the power system is subjected to an abnormal condition such as an overload due to sudden load reconnection, a generator outage or a transmission line tripping, the frequency and voltage instabilities must be quickly addressed [14]. In situations where these abnormal conditions are not addressed in time, the system would experience cascading events which might lead to a blackout [16–18].

Power system protection schemes are the final defense for preventing the cascading events [19,20]. Under frequency load shedding (UFLS) and under voltage load shedding (UVLS) techniques are in use to maintain the frequency and voltage of the system in case of large disturbances. From the onset of frequency/voltage decline, up until the predefined threshold is violated, there is a small time window to implement all required restorative actions [21–23]. Protective schemes have been implemented for different power systems across the world [19]. They are aimed at preventing the system from further separation in the event of a disturbance [20,24]. To achieve this goal, portions of load are carefully relieved from the system until the balance level between the demand and generation is satisfied. If the deficit between the generation and demand still exists, protective schemes must be operated again to achieve a suitable balance; otherwise, the whole, or at least a portion of, the system might face collapse [14]. In such emergency situations, it is better to lose portions of load while maintaining stability of the whole system to avoid undesired collapses. Protection techniques that are properly designed and implemented can bring both economic and technical benefits to the power system operators. To curb the negative effects of blackouts, protective schemes were widely developed and implemented in reality [25–27]. The most commonly referred to protective plan is the one by Western Electricity Coordinating Council (WECC) [28]. This plan was developed in response to three major system-wide disturbances that occurred in 1996. The plan was updated in 2011 to meet modern standards, which indicates the importance of managing frequency to avoid total system collapse. The primary objective of the frequency protection scheme as presented in the WECC plan is to minimize the risk of total system collapse, which can result in socio-economic problems [28].

In order to adhere to standards, power systems' operators have designed protective plans similar to WECC that best suit the nature of their systems. In addition to the protective plans, all of the power system equipment has nominal working conditions and, if these are violated, the equipment might be damaged and result in huge losses to the operators. It is key that all power systems' operators work to improve overall system reliability. A reliable system must be able to meet customer energy requirements on demand. Blackouts pose a question on the reliability of conventional and adaptive protection techniques in avoiding such power outages.

## 1.2. Survey Methodology

It is important to follow a specific methodology for conducting a useful survey on a research topic. In literature, there are some methodologies that have been suggested for concluding useful systematical state of the arts [29–34]. In what follows, the methodology adopted for creating state of the art on power system blackout and cascading events is introduced. It is worth mentioning that the search has focused on the online published materials such as research articles, review papers, conference papers, scientific books, and standards.

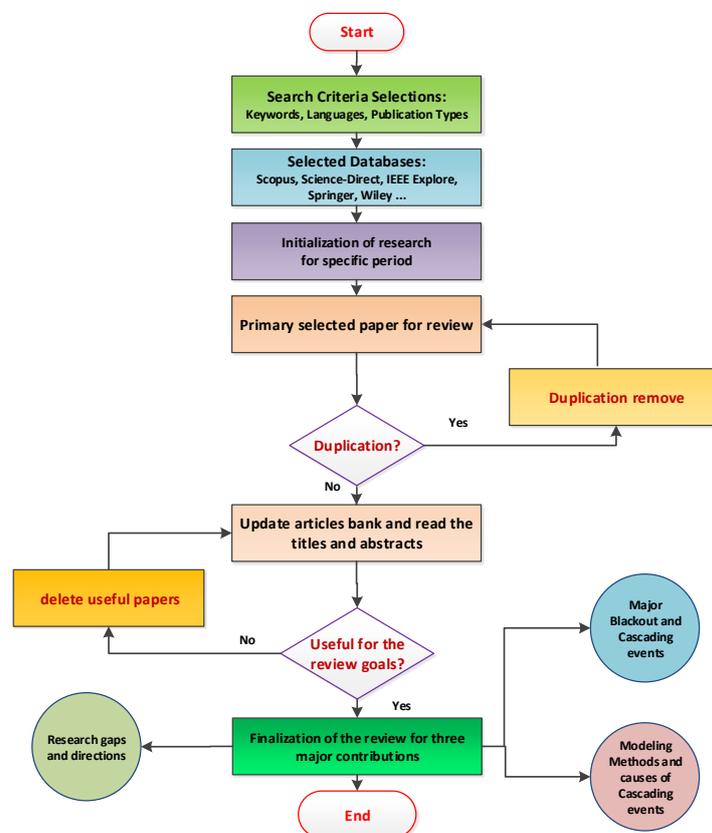
As a first step, databases, i.e., Scopus, IEEE Explore, Science Direct, Springer, Taylor and Francis, and Wiley publishers are comprehensively searched in order to conclude this review. In the search stage, keywords and scientific terms such as “power system blackout”, “power outages”, “power system emergency”, “cascading events”, and “methods for blackout and cascading events” are used. In order

to guarantee the research quality, we have searched for materials published in ISI and “Q1, and Q2” journals. In addition, IEEE conferences’ materials are searched for useful materials. Furthermore, IEEE standards and reports from energy sectors in different countries are carefully checked. The keywords lists, topics of interest, searched databases and other information about the adopted methodology are given in Table 1.

**Table 1.** Terms and searched databases used in the review methodology.

Issue	Criterion
Sector	Electric Power System (EPS)
General Topic	Power system contingency, security and protection
Discipline	Power system failure and disturbances
Very specific topic	Blackout & Cascading Events
Keywords I	Power system emergency, power system security, power system stability
Keywords II	Blackout, power outages, power cuts, cascading events
Language	English (En)
Availability	Online available only
Databases	IEEE, MDPI, Scopus, ScienceDirect, Springer, Wiley, and Taylor and Francis
Publication type	Research articles, Books, Conference papers and Standards

The initial search using the aforementioned review methodology yielded 368 papers, in which 136 papers remained after removing the duplication. In the next step, their titles, abstracts and contributions are checked for removing the unrelated works, which resulted in exclusion of 103 papers. Afterward, the remaining material was screened and fully reviewed by a team of experts on this topic. Figure 1 shows the flowchart of the review process adopted for reaching this comprehensive survey on power system blackout and cascading events.



**Figure 1.** The flowchart of the review methodology used.

As mentioned above, different types of publications are used in this comprehensive review introduced in Table 2. As seen from Table 2, the journal article covers the majority of the reviewed materials, while only 17 conference papers are selected as useful papers.

**Table 2.** Analysis on the literature used in the review.

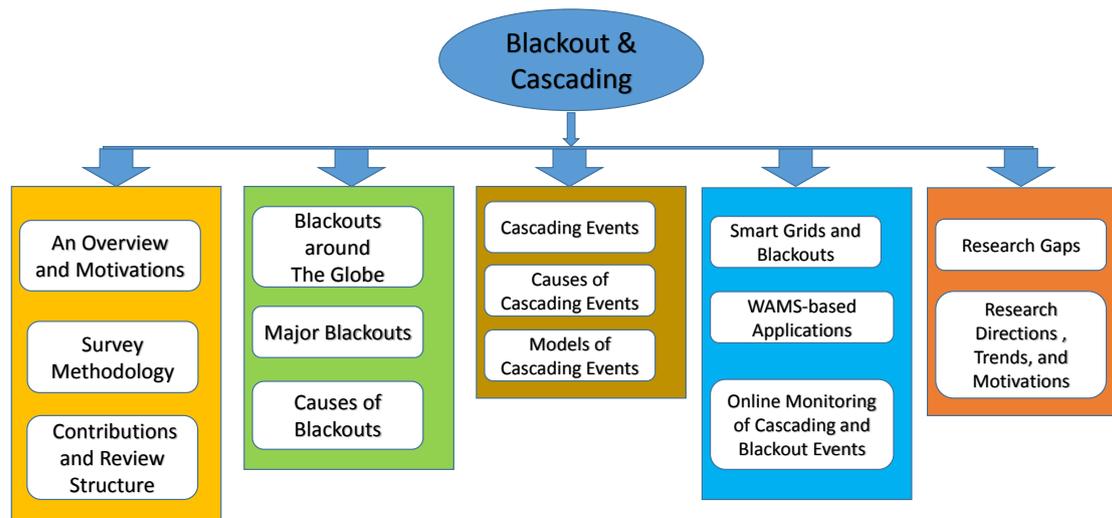
Issue	Number	Percentage
Articles	101	78.29
Conference papers	54	13.17
Standards	8	6.24
Books and book chapters	3	2.3

This review covers the materials that have been published online from year 2001 to 2018. It should be mentioned that the subject of the paper is too specific and we try to survey the major blackout around the globe with more focus on the US Energy system due to the availability of its data and information. In addition, the paper tries to highlight the reasons behind such creditable power outages and cascading events. Furthermore, the analysis of the collected materials shows that there are great research activities in the topic of electric power outages including cascading modeling, and online major event monitoring.

### 1.3. Contributions and Review Structure

In this subsection, the specific topic and main contributions of the paper are briefly introduced. Electric power system contingency and security is a wide research field in which analysis of power outages and cascading failure play a vital role in shaping the future of such systems and guaranteeing their operation in stable and safe mode. Nowadays, power system emergency, security and protection topics have gained considerable attention from researchers for developing new methods that can prevent the cascading failure and avoid blackout and its consequences. In this paper, we mark out three specific points, i.e., a survey on blackouts and their causes, cascading analysis methods, and the importance of emerging technologies such as wide-area monitoring systems. Therefore, we first introduce the most important power system blackouts that have been recorded in the last several decades around the globe. Then, a focus on blackouts in US power systems with analysis study is provided. Furthermore, the causes of blackouts and the methods that can be adopted for modeling the cascading events are reviewed. This paper also highlights the consequences of power system blackout and cascading events for motivating the research in these specific topics. In this review, we mark out the challenges of protective actions used to avoid power system blackout events. Moreover, the research gaps in the topic of power system blackouts and cascading failures are introduced. Finally, some research directions are proposed which can be a good guideline for the researchers. A summary of the paper contribution and its content is shown in Figure 2.

The paper is organized as follows. An overview and motivations of this work is provided in Section 1.1, the methodology adopted for conducting this survey is in Section 1.2, and the paper contribution and organization (Section 1.3) are given in the Introduction (Section 1). A survey on the blackouts around the globe is given in Section 2. Then, a focus is given on the US blackouts in Section 3. The major recorded blackouts around the globe presented in Section 4. Section 5 introduces the major blackout causes. The cascading event modeling and analysis methods are reviewed in Section 6. Section 7 marks out the impacts of blackouts. The research gaps and directions are introduced in Section 8, while Section 9 provides the conclusions.



**Figure 2.** State-of-the-art flow chart of power systems blackout and cascading events: motivations and challenges.

## 2. Blackouts around the Globe

The ability of power systems to maintain stability and to ensure continuous supply of electrical power to customers in the event of a disturbance is of critical importance [5,14]. In light of this fact, when a power system blackout occurs, the consequences can be far reaching. Causes of power system blackouts include transmission line tripping or overloading, control and protection systems mal-operation, lightning strikes on power systems equipment, poor maintenance, human error, voltage collapse, equipment failure, cyber-attacks, quick-frequency declines, and others [5]. As of 2010, several power systems blackouts have occurred, which left millions of customers stranded for hours. For instance, a power outage occurred in the Pacific Southwest on 8 September 2011, which lasted for about 12 h affecting 2.7 million residents of San Diego, California, Arizona and Mexico [35–37]. In this event, tripping of a major transmission line during peak load led to the system collapse. During that time, San Diego experienced a total blackout and simulations in [35] showed that insufficient load shedding led to the cascading effects. Earlier in the same year on 4 February 2011, power system blackout occurred in Brazil due to flaws in the transmission lines and it lasted for about 16 h [38]. About 53 million customers were directly affected [38,39]. On 30 July 2012, a blackout, which lasted for about 15 h, occurred, affecting nearly 620 million residents of the north and east of India [40]. The blackout was due to overloading of one of the 400 kV Gwali–Binar transmission lines while the other transmission line was out for maintenance [41,42]. The system failed again the following day due to demand-generation imbalance and about 700 million people were affected when nearly 32 GW of energy was interrupted [43]. This blackout is the largest power outage in terms of people affected ever-recorded [40]. In Vietnam, a 500 kV line tripped on 22 May 2013, separating the northern and southern grid of Vietnam power system [44]. The same year, in the Philippines, 14 power plants were curtailed affecting their capital city Manila and nearly 40 % of the Luzon islands [45]. The number of affected people was estimated to be 8 million [45]. The tripping of generators and transmission lines led to the overall voltage collapse in the system [45]. A lightning bolt struck the Thailand power system in 2013 affecting almost 8 million people in 14 provinces [44,46]. Bangladesh Power System (BPS) experienced a total system collapse on 1 November 2014, which lasted for about 24 h [47]. According to findings in [47], this was due to unplanned high voltage direct current (HVDC) station outage. The unresponsive spinning reserve and the fact that some generators were under-maintenance worsened the situation [47]. The total amount of load shed after all the under frequency load shedding (UFLS) stages were activated was less compared to the disturbance that was experienced and this led to the blackout [47]. An improvement of the BPS load shedding scheme was proposed as a long-term

solution in case of similar outages in the future in [47]. The power outage in BPS affected almost 150 million people. A technical fault at a power station in Sindh affected nearly 140 million people in Pakistan on 26 January 2015 [10,48–50]. In Turkey, nearly 70 million people had to endure power outages on 31 March 2016 due to power system failure [51]. Nevertheless, some regions which are linked to the Iran power network such as Hakkari and Van did not experience the blackout [51]. About 10 million Kenyans had their power supply interrupted for more than 4 h on 7 June 2016 when a monkey fell on a transformer in Gitaru hydro power station leading to the subsequent tripping of the transformer and interrupting 180 MW of power [52,53]. Uncontrolled events following the 180 MW power loss worsened the situation and led to system collapse [53].

Table 3 shows the number of power outages recorded across the globe in 2011. The average duration for each outage is given in hours in the same table. From the Table 3, it can be seen that, regardless of the lower number of outages recorded in Latin America and Caribbean, the average time taken during each outage was much longer than the other areas. About 1200 power outages with a much lesser duration were experienced in South Asia. The table is to show the reality of the wide prevalence of power systems blackouts across the globe. Based on a report published by Eaton in 2015, a total of 1673 power outages were recorded out of the selected top 10 most affected states in the USA [54]. Due to its high number of recorded blackout and cascading events, the US energy system is the focus of the next section.

**Table 3.** Number of power outages recorded in different parts of world in 2011 [55].

Region	Number of Power Outages	Duration of Each Power Outage (hours)
East Asia and Pacific	200	6.00
Eastern Europe and Central Asia	100	6.50
Latin America and Caribbean	40	8.00
Middle East & North Africa	50	4.00
South Asia	1200	2.50
Sub Saharan Africa	210	7.50
The rest of the countries	250	5.00

### 3. US Blackouts

In this section, we consider some of the blackouts that have occurred in the USA. Table 4 shows the total number of blackouts recorded in the USA from 2008 to 2015 [54,56]. The least amount of power outages was 2169, recorded in 2008 and it left 25.8 million people stranded. The following year, 2840 outages were recorded and 13.5 million people were affected [54]. This was the least number of people affected as recorded from 2008 to 2015 [56]. Out of the 3149 outages that occurred in 2010, 17.5 million people were affected [54]. The highest recorded number of people affected was 41.8 million when 3071 outages occurred in 2011. In 2012, 2808 outages were recorded leaving 25.0 million people without power. Of the 3236 power outages that occurred in 2013, 14.0 million people were affected. The largest number of power outages occurred in 2014 and 14.2 million people were affected [56]. Lastly, in 2015 out of the 3571 recorded power outages a total of 13.2 million people were affected [56]. The numbers are just not mere statistics but indicate the severity of the recorded power outages. Even though Table 4 focuses on the number of outages and the people affected, the impacts of these outages can be far reaching [57]. USA is used as a case study example but different countries across the globe experience similar power outage with some resulting in the total collapse of the power system.

Table 5 shows the summary of the recorded outages in 2015 [56]. Of the 3571 recorded outages a total of 13,263,473 customers were affected. In total, the outages lasted for approximately 122 days in terms of lost time [54]. An average of 3714 people were affected per each outage that occurred and each outage lasted for at least 49 min [54]. The loss in monetary value amount to billions of US\$ [54].

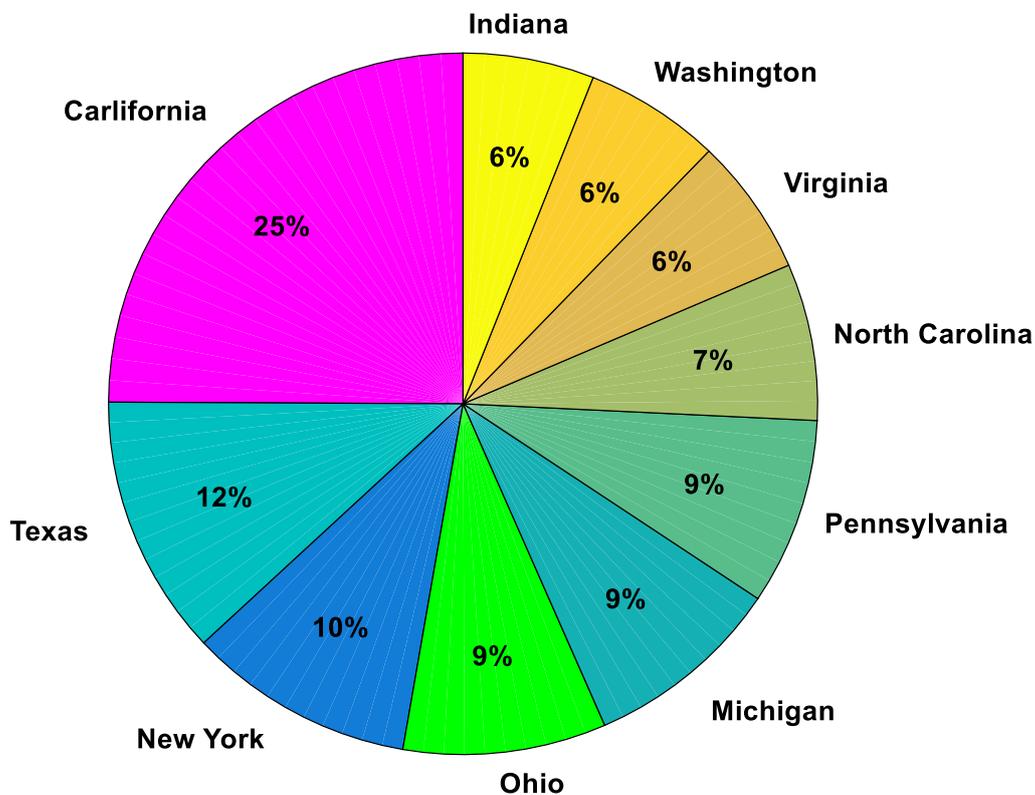
**Table 4.** The total number of blackouts recorded in the USA from 2008 to 2015 [54,56].

Year	Total Number of Outages	People Affected (million)
2008	2169	25.8
2009	2840	13.5
2010	3149	17.5
2011	3071	41.8
2012	2808	25.0
2013	3236	14.0
2014	3634	14.2
2015	3571	13.2

**Table 5.** A summary of the recorded outages in 2015 in US [54,56].

Issue	Criterion
Total number of people affected by outages	13,263,473
Total duration of outages	175,821 min
Total number of outages	3571
Average number of people affected per outage	3714
Average duration of outage	49 min

Of the 3571 outages recorded in 2015, we also considered the top ten states with the highest number of recorded outages [54]. In Figure 3, it can be seen that California was the most affected with 417-recorded outages which is about 25% of the recorded outage. Indiana had the least amount of recorded outages amounting to 100 in the same year. From the analysis of blackouts, the major cause was weather conditions. Therefore, the areas with the highest number of outages indicated areas that had more abnormal weather conditions.



**Figure 3.** Blackout events in different USA states [54].

In what follows, we show the major causes and events that might lead to a blackout situation. We firstly highlight the significant causes that led to blackouts in USA in 2015. As explained earlier, power outages affect millions of customers and have serious further economic effects [54,56,58,59]. Generally, the causes of power outages range from natural disasters, aging power systems, and maloperation of protection systems or operators. Some of the major causes of power system blackouts as recorded in the USA in 2015 are described in what follows. On 17 November, a windstorm with a speed of about 70 mph destroyed electrical power lines leaving nearly 180,000 customers affected [54,56]. Trees falling on electrical power lines further worsened the effect. A storm which was classified as more severe than Hurricane Sandy left 280,000 people without power after destroying electrical power infrastructure on 23 June [54]. During the same period, 250,000 customers were affected in the Philadelphia region [54]. A power outage, which was caused by an underground fire on 15 July, left 30,000 people without power [54]. Further investigations indicated that the problem was aging equipment. An increased demand of power on 20 September when the weather temperatures were very high led the utility to curtail some loads in order to balance the generation and demand. About 150 MW of power was curtailed, leaving 115,000 San Diego customers without power [57]. On 7 April, a metal said to have broken loose from a power line at a switching station led to the interruption of power supply from two power stations [56]. Thousands of people were affected in Washington DC and Maryland. On 14 July, Birmingham experienced severe power cuts due to bad weather. A frosty storm which hit Oklahoma city on 28 November led to power cuts which affected 110,000 residents [54]. The main reason was that power lines were coated with ice to an extent that they became heavy and broke. Similarly, on 14 February, a cold front which brought severe winds of over 50 mph left 103,000 customers in need of power [56]. On 24 December, 60 mph winds led to power cuts leaving nearly 105,000 homes and businesses without power.

#### 4. Major Recorded Blackout Events

##### 4.1. Major Blackout in the U.S.-Canadian System

The most severe major blackout that occurred in the U.S.-Canadian grid was the blackout on 14 August 2003 [58,60–64]. At least 50 million people were affected out of the eight U.S. states and two Canadian provinces affected. An estimated 63 GW of power was curtailed [61]. This power is nearly 11% of the total demand of the Eastern interconnection of the North America system [61]. According to the reports published, more than 400 transmission lines and 531 generating units at 261 power plants tripped. Before the event, the system is said to have been operating according to the North American Electric Reliability Council (NERC) standards [65,66]. Nevertheless, reactive power supply challenges had been noted before. Another issue was of the faulty operating of a Midwest ISO (MISO) state estimator and the real-time contingency analysis (RTCA) software [67]. These software problems together with others led to the unavailability of the real time system information. Outage of the Eastlake Unit 5 generator was initially recorded. This unit and other units in Northern Ohio had been operating under stressed reactive power conditions [61–63]. The units were producing high reactive power outputs and this led to the tripping of the voltage regulator to manual due to over excitation. After intervention by the operator to try to restore the voltage regulator to automatic, the unit then tripped [64]. Cascading faults further followed, leading to a severe blackout. Coincidentally, three 345 kV transmission lines also tripped after contact with a tree further worsening the disturbance situation. Cascading faults further followed with many 345 kV lines tripping due to overload at under voltage. Furthermore, out of step oscillations resulted and the system split into several islands leading to a severe blackout [68]. The task force on power outage conclude that the major cause of this blackout was inadequate understanding of the system and lack of situation awareness [62,64]. Other challenges were poorly maintained vegetation and lack of support from the reliability coordinator.

#### 4.2. Major Blackout in the Swedish-Danish System

A blackout occurred on 23 September 2003 in the Swedish/Danish system [64,69]. The system was operating under normal conditions, but some system components and two 400 kV transmission lines and HVDC links that connect this system with continental Europe were out of service on maintenance [70,71]. Regardless of these conditions, the system was not heavily loaded. The initial failure started when a 1200 MW nuclear unit in southern Sweden tripped due to problems with a steam valve [69]. Even after this failure, the system was still operating normally, but a few minutes later a double bus bar fault occurred at one of the substations [69]. Consequently, some lines were lost and other units also tripped. Under these conditions, the only line left was the 400 kV transmission line which transfers power from north to south [69]. The line was heavily loaded and later failed and caused system separation due to voltage collapse. The south of Sweden and the east of Denmark were separated [69]. In both countries, a total of about 6500 MW was lost affecting, almost 4 million customers.

#### 4.3. Major Blackout in Italy

In addition occurring on 23 September 2003 in Italy, a tree flashover caused the tripping of a major tie-line between Italy and Switzerland [45,72–76]. The failures started to progress when the automatic breaker failed to reclose the line [72]. The synchronization failed due to the phase angle differences. According to [68], the tripping of 380 kV Lukmanier line was initially recorded at 03:01:20. About 25 min later, another 380 kV San Bernadino transmission line was interrupted after delays in power re-dispatching [45,68]. The effects continued and the Italian system lost synchronism with the other parts of Europe. A cascade tripping of 16 transmission lines to Italy was recorded. The tripping was due to system overload and instabilities. After the continued system separation, the Italian power system was left with a deficit of almost 6400 MW [72,73]. The system frequency started to fall and was not corrected in time leading to the total collapse of the Italian power system [73].

#### 4.4. Major Blackout in India

The largest blackout in terms of lost power and affected people occurred in India in 2012 [77–80]. India is the third largest power producing country after China and USA with a yearly production of 1423 TWh [41,78]. The Indian grid has experienced several power blackouts with the worst experienced in 2012. During the summer of 2012, extreme weather conditions led to a high demand in power for cooling systems. In the same season due to limited water supplies, the hydro power plants were generating below their full capacity [41,42]. On 30 July 2012, around 2:00 a.m. in the morning, a 400 kV Gwalior–Binar circuit breaker tripped, triggering a series of events, which later led to a system collapse [42,43]. The major power stations in the area were affected leading to a loss of 32 GW in generated power. Because of this power loss, nearly 300 million customers were left without power. Serious consequences were experienced due to this power loss. Railways, airports, passenger trains and traffic signals were all shutdown causing commotion in business areas [42]. Hospitals without reliable power back up supplies had to endure 3 to 5 h of no power. After restorative actions, about 80% of the power was restored after almost 15 h [43]. The following day on 31 July, at around 1:02 p.m., the power system experienced another disturbance [43]. This was due to a relay problem near the Taj Mahal and several power stations were again grounded [41,43]. More than 600 million individuals lost their power. The failure severely affected the basic infrastructure facilities like railways, metro rail system, lifts in multi-storey buildings, and movement of vehicular traffic. Some miners were trapped underground and had to be later rescued, passengers traveling with the metro had to be rescued as well. An investigation that was carried out later on after these disturbances had occurred drew conclusions on the cause. The first cause was of the weaker power transmission line. As of 29 July, the high loading of the Gwalior–Binar led to the tripping action [41–43]. The failure to respond in time of the state load dispatch centers to manage the power flows led to the line tripping.

#### 4.5. Major Blackout in the Brazilian Grid

Though not very common, power outages continue to be witnessed across the globe. The main challenge with power outages and blackouts is that they lead to heavy economic losses. On 21 March 2018, more than 10 million customers were affected when a power outage struck the Brazilian power system [39,81–83]. The power outage started at 3:40 p.m. due to a failure of a transmission line near the Belo Monte hydro power station. About 18,000 MW of power was curtailed during this disturbance [39]. The Brazilian power system demand is mainly supplied by hydro generators and has been studied for years. The first special protection scheme (SPS) was implanted in Brazil in 1974 and it was a three-stage under-frequency load-shedding scheme [84]. In 1975, only five SPS were in operation and, by the year 2005, they had increased to 133. The use of SPS in Brazil was proven to be superior in minimizing the impacts of blackouts from the examined various multiple contingency situations. An upgrade from n-1 to n-2 contingency was also proposed as a possible way of enhancing power systems reliability during disturbances. Other blackouts that occurred in Brazil on 10 November 2009 and 4 February 2011 also lead to recommendations on enhancing the system against major disturbances as well as improving the black-start restoration capabilities [85]. In modern systems, proper maximization of wide area measurement systems can go a long way in improving system reliability.

### 5. Major Blackout Causes around the Globe

Major power outages that affected people around the world from 2011 to 2018 have been comprehensively reviewed. Table 6 summarizes the most well-known blackout and cascading events in this decade. In addition, the blackout duration per hour for each event is given in Table 6. It can be seen that the blackout occurred in Bangladesh on 1 November 2014 has the highest duration of 24 h [47]. The Indian blackout on 30 July 2012 has impacted the highest number of people during history (620 million). The majority of causes of the blackout are related to transmission system operation, control and protection. Other useful information about the major blackouts in this decade are given in Table 6.

**Table 6.** A summary of recorded major (most severe) power outages around the globe in this decade.

References	Country/Region	Date	Duration (hours)	Affected People (million)	Causes
[35,36]	Mexico & the USA	8 September 2011	12	2.7	Transmission line tripping
[38,83]	Brazil	4 February 2011	16	53	Transmission line fault and fluctuated power flow
[41–43]	India	30 July 2012	15	620	Transmission line overload
[44]	Vietnam	22 May 2013	10	10	Crane operator
[45,86]	Philippines	6 August 2013	12	8	Voltage collapse
[44,46]	Thailand	2013	10	8	Lightning strike
[47]	Bangladesh	1 November 2014	24	150	HVDC station outage
[49,50]	Pakistan	26 January 2015	2	140	Plant technical fault
[39]	Holland	27 March 2015	1.5	1	Bad weather conditions
[51,87]	Turkey	31 March 2015	4	70	Power system failure
[88,89]	Ukraine	21 November 2015	6	1.2	Power system failure
[88,90,91]	Ukraine	23 December 2015	6	230	Cyber-attack
[52,53]	Kenya	7 June 2016	4	10	Animal shorted the transformer
[92–94]	Sri Lanka	3 March 2016	16	10	A severe thunderstorm
[95–99]	South Australia	28 September 2016	6.1	1.7	Storm damage to transmission infrastructure & cascading events
[57,100]	the US (NY)	1 March 2017	11	21	Cascading failure in transmission system
[101]	Uruguay	26 August 2017	4	3.4	Bad weather conditions lead to cascading failures
[57,102]	US (southeast)	10 September 2017	5	7.6	Cascading events and transmission tripping
[103–106]	Sudan	10 January 2018	24	41.5	Cascading failures
[107–109]	Azerbaijan	3 July 2018	8	8	Unexpectedly high temperatures
[81–83,110]	Brazil	21 March 2018	1	10	Transmission line failure
[78,111]	Canada (BC)	20 December 2018	4	0.6	Winds reached speeds of 100 km/h

In addition, Table 6 gives a summary of the causes of power cuts and blackouts recorded across the globe [112]. Generally, all these causes end up in transmission line overload and tripping or generator tripping [64,113,114].

Table 7 shows 66 surveyed major power systems blackouts in some parts of the world from 2011 to 2019. The survey is not a comprehensive of all the power systems blackouts in the world but is a good indicative tool in analyzing the causes of power system blackouts. It can be seen that the highest number of blackouts was due to abnormal weather conditions such as severe winds and heavy storms and trees falling on transmissions line. However, bad weather conditions cannot be predicted with absolute certainty, therefore having a forecast of them and an improved power system monitoring a control platform can significantly safeguard power systems against such events.

**Table 7.** Analysis on blackouts around the globe and their percentage from 2011 to 2019.

Blackout Cause	Number Recorded	% of the Recorded Number
Weather/Trees	33	50
Faulty equipment or human error	21	31.8
Vehicle/Accidents	7	10.6
Animals	1	1.5
Over demand	4	6.1
Total	66	100

In power systems, large disturbances are usually followed by series of events called cascading events. If these events are not well managed, the system would encounter a blackout. However, the initiating conditions vary and may include bad weather, animals shorting system equipment, operation errors or technical faults indicated under major causes of power systems collapse. Whenever a power system disturbance occurs, a deficit between the generation and the demand occurs resulting in unsecure operation of the system. This deficit can lead to overloading of generators and transmission lines causing the system frequency and voltages at respective buses in the system to drop. In order to keep the frequency and voltage within acceptable thresholds, emergency load tripping is done through relay action. If the curtailed load is not sufficient or if the relay action is delayed, subsequent transmission lines and generators trip. The situation will dramatically develop into cascading events, which, if not addressed, the system will collapse. From the time of the disturbance until the system collapses, the major physical phenomena of concern are mainly [114–116]:

- Transmission lines overloading or online generator tripping,
- Increase or decrease of the system frequency,
- Power system voltage collapse,
- Generators losing synchronism,
- Growing low-frequency oscillation of large power systems.

In addition to the major physical phenomena of concern, the general events which occur before and after the beginning of a cascade are nearly similar for the major recorded large scale power system blackouts. The main events before the cascade include excessive power transfers and lines tripping by tree contact (or unit tripping) (this occurs at below normal system voltage), which is mainly due to lack dynamic reactive power reserves [68]. In substation bus-bar fault or line fault, the tripping of lines tripping led to reversed power transfers or load transfer to parallel lines. The overall consumption of the reactive power increased. After the start of a cascade, protective relays operated on overload and the system integrity is severely compromised. Impedance relays also operated by out of step oscillation. Generating units also trips on under-frequency or under-voltage. Further investigations show that, in cascade events, the protective relays play a significant role in compounding and propagation of cascading blackouts [68].

Table 8 gives a summarized overview of the initial disturbances and the subsequent cascading events lead to the major blackouts around the globe.

In most cases when a power system is subjected to transmission lines overloading or tripping of connected generators, the frequency begins to decrease and this calls for the operation of UFLS techniques [58,116,117]. Other modern techniques in smart grids include demand side management, fast spinning reserve, and modern energy storage systems. UFLS techniques must be fast enough to arrest frequency decline; otherwise, the system will collapse. The voltage collapse of different bus bars has been also considered as one of the major causes leading to total power system collapse. Due to lack of information of all the systems across the globe, we considered the prevalence of some of the major cause of power outages as witnessed in the US.

There were about seven major causes of power outages recorded in the US in 2015. These causes are weather conditions or trees, too much demand, vehicle accidents, planned outages, faulty equipment or human error, animals and other unknown causes as shown in Figure 4. Weather conditions and trees contributed to the largest number of outages. About 1069 were due to weather conditions and trees. Improperly maintained trees can interfere with transmission or distribution lines leading to their tripping. Weather conditions such as storms, snows or other severe conditions can again affect transmission lines. Another 942 power cuts were due to faulty equipment and human error. Decisions by human operators that are ill timed or wrong can lead to unwanted tripping of units. Plant equipment must be properly and constantly maintained and, if not, can fail during operation leading to unplanned power cuts. Vehicle accidents such as cranes interfering with transmission lines or cars ramming onto power lines poles can interrupt the normal operation of this equipment. In 2015, 419 of these vehicle accidents together with others were recorded [54]. Power system equipment can be taken out on planned outages or statutory maintenance and this reduces the overall reliability of the system in which a disturbance occurring during this period might lead to cascading events, leaving a number of customers without power. Planned outages accounted for about 224 power cuts experienced in 2015. Animals can cause a power cut when they come in contact with energized equipment. In such cases, the electrical path is shorted through the animal body [56]. Of the power cuts recorded, 179 of them were related to animals. During peak hours or when an online unit is tripped, an imbalance between the demand and generation occurs. To prevent the decline of frequency, some system loads are intentionally shed to restore the system to normal operating conditions. Only nine power cuts were a result of over demand in 2015. Lastly, almost 714 power outages were due to unknown causes [54,56]. This poses a huge threat to the secure operation of power systems. There is a need to fully understand the power systems dynamics, causes of disturbances and how they can be prevented in the future.

Although the blackout tracker lists seven major causes of power systems disturbances and blackouts, in [118], eleven causes are stated. The given causes are more specific rather than generalized. The initial causes are primary equipment failure, design and application error, secondary equipment failure, communication and/or control system failures as well as natural phenomena beyond those designed. Other causes include operator errors, errors in maintenance, security related such as cyber-attacks, inadequate investment and complexity of systems, excessive risk taking and/or inappropriate risk management and others, which can be insufficient training of personnel. Of the 33 assessed power system blackouts in [118] the most common causes of system disturbances are natural phenomena, communication/control System failure, design and application error, operator error, primary equipment failure and insufficient training. The major causes in [57], which focus only on the U.S. system and [118], which focus on all continents are similar. It should be noted that the natural phenomena also include the conditions of weather as stated in the U.S blackout tracker.

**Table 8.** An overview of the initial disturbances and the cascading events led to the major blackouts around the globe.

References	Blackout	Initial Cause	Cascading Events
[61,62]	the US & Canada (2003)	East lake Generator tripping due to incorrect data from monitoring system	i—Transmission line trips after contact with a tree ii—Alarm system failure iii—345 kV Chamberli-Harding line sags on to a tree and trips iv—Voltage dips and no AVR action v—Successive line trip due to under voltage
[64,69]	Sweden–Denmark (2003)	1200 MW Nuclear power plant trips due to problems with steam valve	i— A double bus-bar fault on one of the substations ii—Transmission line tripping due to overload iii—Generator tripping due to under frequency iv—400 kV north-south interconnecting transmission line trips
[72,73]	Italy (September 2003)	Tree flashover caused the tripping of a major transmission line	i—Automatic breaker failed to re-close due to synchronization problems ii—380 kV transmission line failure due to delayed re-dispatch of power iii—Loss of synchronism with the other parts of Europe iv—Frequency fell to 49 Hz and then to 47.5 in 2.5 min and generators tripped
[41–43]	India (July 2012)	Circuit breaker on 400 kV Bina-Gwalior tripped	i—Tripping of Agra Bareilly breakers ii—Power failure cascading through the grid due to under voltage iii—The following day a relay failure occurred near Taj Mahal iv—Power stations across affected parts went offline
[44,46]	Thailand (2013)	Failure in major AC tie-line	i—A 500 MW power station was interrupted ii—Major tie line for power distribution was affected iii—Further system generator tripped on under voltage and frequency
[47]	BPS (November 2014)	HVDC lines outage	i—Insufficient load shedding ii—Subsequent generator tripping on overload iii—Transmission lines disconnection due to under voltage
[52,53]	Kenya (June 2016)	Monkey led to tripping of the transformer	i—Generators at the plant tripped on overload ii—180 MW lost from Gitaru iii—Voltage drop led to subsequent transmissions tripping

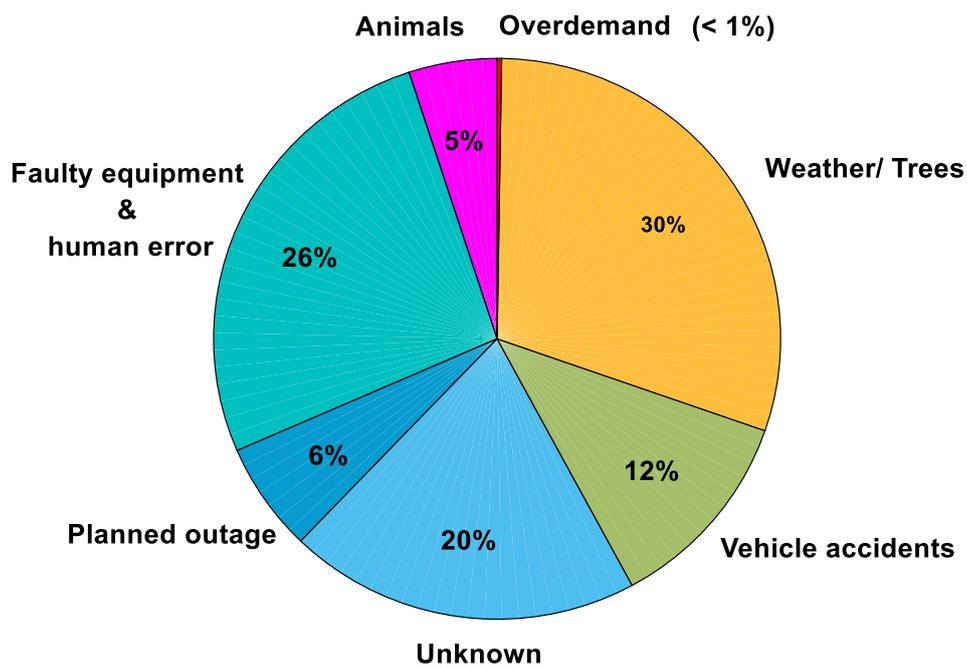


Figure 4. Major electric power system blackout causes [54,56,57].

## 6. Cascading Event Modeling and Analysis

Several critical cascading failures have been recorded in literature; therefore, it is of great importance to come up with appropriate models which helps to identify the critical initial disturbances, and helps to eliminate the cascading blackout of power systems in advance. Initially, the cause and the cascading process of blackouts must be known. Generally, a blackout usually starts as a single system failure, which can, in turn, lead to cascading failures [119–121]. These cascading blackouts leave many people affected and can result in heavy economic losses.

Before making the model, figuring out the cause and process of cascading blackout in power systems is essential. Based on the literature review, there are three types of main models that characterize power systems cascading failures. The first type of the models only describes the topological properties of power networks and ignores the underlying laws of physics and the principles of electrotechnics [122,123]. The second type of model considers the quasi-steady-state of power systems and calculates the power flow by solving the direct current (DC) or the alternate current (AC) power flow equations [124–126]. The third model focuses on investigating the emergence of cascading failures through dynamic modeling of power system components [127,128]. Nevertheless, the approaches of complex networks analysis in power grids was studied by [129] and it was deduced that it is necessary to incorporate the physical and electrical properties. In previous decades, researchers from various fields were attracted to coordination and control of multi-agent systems [130–132]. Since a bus in power grids can be considered a smart agent able to communicate and interact with its neighbors, a multi-agent system approaches can be applied to power system control and protection as in [133].

It is important for the industry and research institutions to have a thorough knowledge about the cascading outages [117]. Electrical power systems cover vast geographical areas and consist of different types of equipment inter-linked together. Due to this structure and nature, it is difficult to comprehend the way by which cascading outages evolve [120]. In this regard, researchers have come up with a variety of cascading failure-modeling approaches [117,134]. The most common approach for analyzing cascading failures is the quasi-steady-state (QSS) DC power flow models [119,135,136]. These models are simple and robust in describing cascading overloads. The major challenge with QSS-DC power flow is that they fail to capture nonlinear mechanisms. To model these nonlinear mechanisms, such as voltage collapse or dynamic instability, QSS-AC power flow models are used.

In [137–141], QSS-AC power flow models are used in cascading effect analysis. Even though they can handle nonlinear effects, QSS-AC models have convergence problems. As a result, they require some assumption in machine modeling. In [140], a combination of both DC and AC models is proposed. This allows the under frequency load shedding and under voltage scenarios to be accurately modeled. These techniques are more superior to DC models but do not account for the effects of voltage collapse. Some proposed techniques rely on historical or simulation data to come up with the overall features of the cascading effects [141–143]. The techniques are generally known as statistical methods. In [132,133,144,145] topological models have been proposed. However when applied to power systems' vulnerability assessment, they require enough grid information; otherwise, the results will be useless [136]. To understand the mid- to long-term stability impact on cascading outages, dynamic and numerical techniques have been applied [146–149]. It is important, however, to also do concurrent modeling of the system dynamics and the protection operation as in [150].

## 7. Impacts of Blackouts

Unplanned power outages and blackouts have significant impacts on businesses operating in the affected areas [151–153]. Human activities globally are highly dependent on power supply to an extent that, when a power system collapses, many effects are experienced [63,152,154,155]. In Figure 5, it can be seen that power blackouts have social, economic and political impacts on today's human activities.

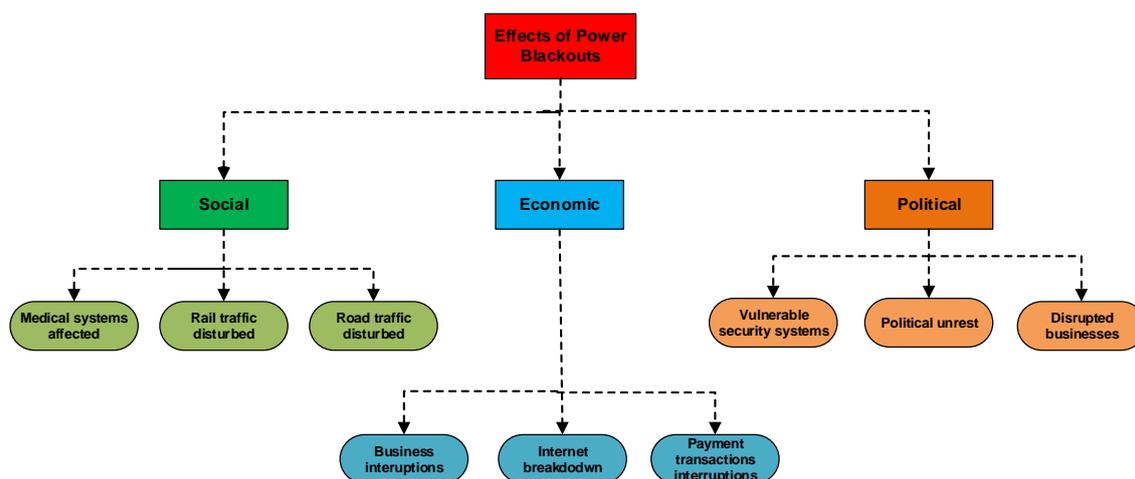


Figure 5. Major electric power system blackout causes.

Socially, when a blackout is experienced, medical systems, rail and road traffic systems are heavily affected [151,156]. Facilities in big cities and towns, like water supply, depend on electricity to treat and pump water for domestic and industry use. The loss of power results in such facilities grounding to a halt. Loss of water for big cities pose a big health risk—for example, in some countries, outbreaks of diseases occur, which can take lives in a matter of hours. Vaccines and drugs that require refrigeration are at risk in the event of a prolonged blackout. The loss is also in monetary value, as new vaccines and drugs will be needed for replacement, creating artificial shortages for people in need of such drugs. Modern equipment in hospitals like X-rays, ventilators and theaters depend on electricity, thus paralyzing the hospital and causing danger to life [157]. The use of backup generators, which have a high cost, is also a financial burden on the already expensive costs of accessing health to a majority of people in the world. The backup generators require continuous maintenance and testing to ensure they will work in the event of a power outage. Patient data and lives are all on the line when the power goes out. In addition, without working telephone lines, people will not be able to call emergency services for help.

In business, huge economic losses occur due to internet breakdown, failure of payment systems and down time of manufacturing and production industries [151,158,159]. Industries, despite having backup generators, can still lose production hours resulting in losses in revenue from failing to meet demand or targets. Ports of entry (sea/air/road/rail) drive economies and heavily depend on electricity from control towers to handling containers that require cranes to move goods. The delay in loading/offloading of goods at seaports can have cascading effects i.e., critical goods like oil, medicines, and food. Perishable goods at ports are at risk due to a loss of refrigeration and delay in shipping or delivery [151,160,161]. Data center infrastructure that supports an organization's IT operations are also affected. Data centers store, organize, manage and process a company's information/data. The loss of data center due to a power outage results in loss of mission-critical data. Companies in the 21st century rely heavily on data stored in their data centers, and losing this crucial information could have long-term effects on the company's daily operations. An example of this is that most project teams in an organization depend on these data centers to operate from different places across the world, thus also resulting in time lost in implementing projects causing delays and poor customer satisfaction. Financial companies involved in the stock market can lose out on thousands/millions of dollars in seconds due to blackouts. Transactions happen every second; even a short-term outage can have a drastic impact on businesses on the stock market. Companies in the retail industry suffer lost sales revenue with unplanned outages. For larger retail companies, a few minutes of downtime can lead to tens of thousands of dollars in lost revenue. The loss come from the loss in possible transactions and from perishable goods that require refrigeration.

Agriculture in the 21st century has become heavily dependent on mechanization to reach sufficient yield required to feed the growing population. Critical equipment such as irrigation makes use of pumps to get water from boreholes and rivers for crops and animals to process the harvest. The loss of power can cause devastating loss to a farmer in the line of farm production [162]. The blackouts also have even more serious impacts on the utility companies that are required to deal with the blackouts [163,164]. The blackouts have effects on costs from litigation, loss of equipment, overtime works for the employees, loss of generation and loss of revenue. The hydro plants can quickly recover from blackouts, but thermal plants take longer to bring units back online, and high costs of startups after a black out are experienced.

During a blackout, the security systems are disabled, and, if there are no standby power sources, this can be a political threat to a nation [58,165]. Electricity is used to operate military bases where government officials work to support and maintain deployment of weapons and oversee combat forces. The equipment also includes data centers, and outages can cause valuable weaponry and equipment to become useless in the event of an attack [154,166,167]. With non-functioning equipment, military personnel could be left defenseless from attacks. The bases may have also important facilities like airports and hospitals that also require electricity.

## 8. Research Gaps and Directions

It is with a great importance to present the most critical, practical and research gaps in the field of blackout and cascading studies in modern and future smart grids. By presenting such gaps, the future studies of blackout and design of the protective function would be better shaped. Therefore, we start with introducing the research gaps of blackout studies topic in Section 8.1, followed by some research direction for solving such gaps in Section 8.2.

### 8.1. Practical Challenges and Research Gaps

Traditional power systems have been known as vertically integrated utilities. In these types of power systems, one utility had a monopoly on the industry and handled all the functions. The operation and coordination of generation, transmission and distribution within a certain geographical area were under a single operator. Protective functions were simple and easily implemented without facing many challenges [1,124,168]. In contrast to traditional power systems, modern power systems

face new complexities. Due to the ever-increasing demand for energy, modern power systems are usually operating near the steady state stability margins [169]. In case of major imbalance, the power systems do not have enough reserve/time to close the deficit and this may lead to cascading failures. To compensate the increasing demand and reduce the effects of conventional generation units, many countries have increased the penetration of renewable energy resources in their systems. Such high penetration results in high reduction in the total system inertia, which leads to noticeable fluctuation in the frequency and active power.

The main challenge in modern power systems is the existence of the traditional protective functions that can not adapt to the deregulation concept and the new types of generations. Unfortunately, there is no coordination between the different protective functions that result in erroneous operation. In some practical cases, it has been shown that the maloperation of some protective functions is the main reason behind blackouts. Therefore, the reliability of both control and protective functions need further investigations and improvements. The reliability is another important factor and has a direct impact on the occurrence of blackout and cascading events [16,170,171]. One element with low reliability rate is enough to make the overall reliability of the system worse. Therefore, there is a need for online assessment of the overall reliability of the system in order to reduce the power outage rate in modern power systems.

These are some of the challenges and gaps, which still need thorough attention of researchers in the implementation of control and protective schemes in order to reduce the power outages in modern power systems and future smart grids. The aforementioned most recent practical challenges associated with protective and operation functionalities are presented below as research gaps as follows:

- Considering the high penetration of renewable energy resource and distributed generation in blackout studies and planning of power system protection schemes.
- Considering the fluctuations of some important parameters in the modern power systems such as total inertia, damping coefficient, and stability indices.
- Investigating other indices for online stability and reliability assessment.
- Online coordination of the different control schemes in power systems can help with reduction of power outages.
- Online coordination of the different protective functions has a direct impact on the rate of blackout cascading events.
- Considering the real-time monitoring technologies for improving decision-making in the emergency situations in power systems.
- Investigating the ability of wide-area measurement systems in improving the reliability and security of the modern power system.
- Investigating the possibility of online coordination of protective functions for improving their performance in modern and future power systems.
- Considering the smart grid features in future protective function design.
- Proposing new protective methods that make use of wide area measurement system (WAMS) technologies.
- Increasing the protection against the cyber-attack issues.

## 8.2. Future Research Directions

Currently, there are noticeable research activities in investigating the ability of WAMS in providing new tools for online assessment of power system reliability, monitoring, and security [172–175]. The main point that can be raised in this topic is improving the dynamic and static monitoring of power systems during the disturbance and maloperation situations. There is a great need for reducing the time of a decision-making stage during the emergency situations. The future power system is in need of modern protective functions and schemes that can update their coordination online where

the maloperation of protection schemes during the emergency state was one of the main reasons for blackout and cascading events.

Smart grid and WAMS technologies can provide effective solutions for reducing the blackout rate in modern and future smart power systems. In this regard, the smart grid enables demand side participation in providing some ancillary services for independent system operators (ISOs) such as primary and secondary reserves, and emergency demand response. The activation of such services might bring some advantages such as improving the stability margin and giving more time for decision-making during the emergency stage for choosing the best solution. Likewise, the infrastructures of modern power systems need more investigations in order to implement new technologies for avoiding the cascading events.

Electric system authorities in some countries have recently reported that their systems are under possible risk due to cyber-attack issues. It has been reported that some blackouts occurred due to cyber/physical attack issues. Therefore, there is a need for proposing new tools and protective functions that can prevent or at least mitigate the impact of such issues in modern power systems.

## 9. Conclusions

In this paper, the state of the art on blackout and cascading events in modern power systems is presented. Due to their importance, blackout and cascading events in power systems around the globe are completely reviewed. Different causes and reasons behind the different blackout in power systems are marked out. Furthermore, classical and modern methods for modeling the cascading events are surveyed. The challenges in protective functions and research gaps related to power systems blackout and cascading failures are highlighted. Finally, some research directions in the topic of modern load frequency control systems are proposed as motivation for research in this important topic. The main points that can be derived from this survey are:

- Most power system blackouts start due to bad weather followed by subsequent cascading events; therefore, weather forecasting techniques must be updated and power systems operators must have this information to prepare for such events.
- The other major cause was faulty equipment and human error, power system equipment is rated to operate under specific conditions and for specific durations before periodic checks or planned maintenance. These issues must be emphasized in power systems and standards adhered to.
- An upgrade of the power system monitoring, control and protection schemes is required to enhance system reliability. The wide area measurement systems (WAMS) platform is one of the promising platforms.
- Customers must be encouraged to participate in the demand side management programs such as the emergency demand response.
- Reserve management of most power systems must be improved—at any time, a specific share of generation must be allocated as a reserve. Ways to minimize the initial costs of renewable energies to be found and renewables must be used to supplement conventional generation.
- Pre-disturbance systems studies must be done and also include the possible cascading events.
- UFLS techniques must be improved so that they can quickly respond and shed enough load in emergencies.

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## Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternate Current
AI	Artificial Intelligence
ACE	Area Control Error
AE	aqua Electrolyzer
AGC	Automatic Generation Control
BPS	Bangladesh Power System
DC	Direct Current
FACTS	Flexible AC Transmission System
HVDC	High Voltage Direct Current
QSS	Quasi-Steady-State
RTCA	Real Time Contingency Analysis
SG	Smart Grid
MISO	Midwest ISO
NERC	North American Electric Reliability Council
DG	Distributed Generation
PMU	Phasor Measurement System
UFLS	Under Frequency Load Shedding
UVLS	Under Voltage Load shedding
WAMS	Wide-Area Measurement System
WAMCPS	Wide-Area Monitoring, Control, and Protection System
WECC	Western Electricity Coordinating Council

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