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Introduction

1.1 Importance of Modeling and Understanding Cascading Failures

1.1.1 Cascading Failures

Cascading failures can happen in many different systems, such as in electric power systems [1–7], the Internet [8], the road system [9], and in social and economic systems [10]. These low-probability high-impact events can produce significant economic and social losses.

In electric power grids, cascading blackouts are complicated sequences of dependent outages that could bring about tremendous economic and social losses. Large-scale cascading blackouts have substantial risk and pose great challenges in simulation, analysis, and mitigation. It is important to study the mechanisms of cascading failures so that the risk of large-scale blackouts may be better quantified and mitigated. Cascading blackouts are usually considered rare events, but they are not that uncommon. The frequency of these high-impact events is not as low as expected. The following is a subset of the very famous large-scale blackouts around the world.

- 1965 Northeast blackout: There was a significant disruption in the supply of electricity on November 9, 1965, affecting parts of Ontario in Canada and Connecticut, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Pennsylvania, and Vermont in the United States. Over 30 million people and 80,000 square miles were left without electricity for up to 13 hours [11].
- 1996 Western North America blackouts: A disturbance occurred on July 2, 1996, which ultimately resulted in the Western Systems Coordinating Council (WSCC) system separating into five islands and in electric service interruptions to over two million customers. Electric service was restored to most customers within 30 minutes, except on the Idaho Power Company (IPC)

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system, a portion of the Public Service Company of Colorado (PSC), and the Platte River Power Authority (PRPA) systems in Colorado, where some customers were out of service for up to 6 hours [12]. The first significant event was a single phase-to-ground fault on the 345-kV Jim Bridger–Kinport line due to a flashover (arc) when the conductor sagged close to a tree. On July 3, a similar blackout occurred, also initiated by the tree flashover of the 345 kV Jim Bridger–Kinport line.

- 2003 U.S.-Canadian blackout: A widespread power outage occurred throughout parts of the northeastern and midwestern United States and the Canadian province of Ontario on August 14, 2003, affecting an estimated 10 million people in Ontario and 45 million people in eight U.S. states [13]. The initiating events were the out-of-service of a generating plant in Eastlake, Ohio, and the following tripping of several transmission lines due to tree flashover. Key factors include inoperative state estimator due to incorrect telemetry data and the failure of the alarm system at FirstEnergy’s control room.
- 2003 Italy blackout: There was a serious power outage that affected all of Italy – except the islands of Sardinia and Elba – for 12 hours and part of Switzerland near Geneva for 3 hours on September 28, 2003. It was the largest blackout in the series of blackouts in 2003, affecting a total of 56 million people [14]. The initiating event was the tripping of a major tie line from Switzerland to Italy due to tree flashover. Then a second 380-kV line also tripped on the same border (Italy–Switzerland) due to tree contact. The resulting power deficit in Italy caused Italy to lose synchronism with the rest of Europe, and the lines on the interface between France and Italy were tripped by distance relays. The same happened for the 220-kV interconnection between Italy and Austria. Subsequently, the final 380-kV corridor between Italy and Slovenia became overloaded and it too was tripped. Due to a significant amount of power shortage, the frequency in the Italian system started to fall. The frequency decay was not controlled adequately to stop generation from tripping due to under-frequency. Thus, over the course of several minutes, the entire Italian system collapsed, causing a nationwide blackout [15].
- 2012 Indian blackout: On July 30 and 31, 2012, there was a major blackout in India that affected over 600 million people. On July 30, nearly the entire north region covering eight states was affected, with a loss of 38 000 MW of load. On July 31, 48 000 MW of load was shed, affecting 21 states. These major failures in the synchronously operating North-East-Northeast-West grid were initiated by overloadin of an interregional tie line on both days [16–18].
- 2015 Ukrainian blackout: On December 23, 2015, the Ukrainian Kyivoblenergo, a regional electricity distribution company, reported service outages to customers [19]. The outages were due to a third party’s illegal entry into the company’s computer and supervisory control and data acquisition (SCADA) systems: Starting at approximately 3:35 p.m. local time, seven 110-kV

and 23 35-kV substations were disconnected for 3 hours. Later statements indicated that the cyber-attack impacted additional portions of the distribution grid and forced operators to switch to manual mode. The event was elaborated on by the Ukrainian news media, who conducted interviews and determined that a foreign attacker remotely controlled the SCADA distribution management system. The outages were originally thought to have affected approximately 80,000 customers, based on the Kyivoblenergo's update to customers. However, later it was revealed that three different distribution companies were attacked, resulting in several outages that caused approximately 225,000 customers to lose power across various areas.

- 2016 Southern California disturbance: On August 16, 2016, the Blue Cut fire began in the Cajon Pass and quickly moved toward an important transmission corridor that is composed of three 500-kV lines owned by Southern California Edison (SCE) and two 287-kV lines owned by Los Angeles Department of Water and Power (LADWP) [20]. The SCE transmission system experienced 13 500-kV line faults, and the LADWP system experienced two 287-kV faults because of the fire. Four of these fault events resulted in the loss of a significant amount of solar photovoltaic (PV) generation. The most significant event related to the solar PV generation loss occurred at 11:45 a.m. Pacific Time and resulted in the loss of nearly 1200 MW.
- 2016 South Australia (SA) blackout: On September 28, 2016 there was a widespread power outage in SA power grid which caused around 850,000 customers to lose their power supply [21]. Before the blackout the total load including loss in the SA power grid was 1826 MW, among which around 883 MW was supplied by wind generation, corresponding to a very high renewable penetration [22]. Late in the afternoon a severe storm hit SA and damaged several remote transmission towers. The SA grid subsequently lost around 52% of wind generation within a few minutes. This deficit had to be compensated by the power import from the neighboring state, Victoria, through the Heywood AC interconnection. The significantly increased power flow was beyond the capability of the interconnection. Ultimately the SA system was separated from the rest of the system before it collapsed [22].

Some of the past cascading blackouts share similarities. For example, the two significant outages in the western North America in 1996 [12], the U.S.-Canadian blackout on August 14, 2003 [13], and the outage in Italy on September 28, 2003 [14], all had tree contact with transmission lines [23]. Modeling and understanding these common features will help prevent future cascading blackouts that might be initiated by the same reason. At the same time, each blackout has its own unique features due to the characteristics of the particular system, which makes the modeling and understanding of cascading failures challenging.

1.1.2 Challenges in Modeling and Understanding Cascading Failures

The modeling and understanding of cascading failures, or in particular cascading blackouts, can be very challenging in the following aspects:

- 1) Size of the system: The size of the interconnected power system can be very large. For example, in the United States utility companies build power system models, which are then used to create the North American Electric Reliability Corporation (NERC) interconnection-wide models, with over 50 000 buses. Modeling and understanding the possible ways that such a big system fails can be really challenging.
- 2) Limited computational power: The computational power is constantly improving as technologies for both hardware and software advance. However, it is still very limited. Although $N - 1$ contingency analysis is usually achievable, even only $N - 2$ contingency analysis for a system with thousands of components can lead to formidable computational burden [24].
- 3) Mechanisms in cascading blackouts: There can be many mechanisms during a cascading blackout, which can include thermal dynamics of the transmission line and tree contact, human error, power flow redistribution, protection misoperation, voltage collapse, transient instability, oscillation, and so on [25].
- 4) Complexities of the system: The power system is not only large but also very complex. The components in the power system can have very complex, tight, and even poorly understood interactions. As mentioned in Perrow [26], from the perspective of complex systems, the system-level failures are not caused by any specific event but by the property that the components in the system are tightly coupled and interdependent of each other. Therefore, complex and difficult to understand component interactions make it difficult to capture the failure propagation patterns [5, 27, 28].
- 5) Evolving system: The power system is evolving all the time. As the economy and the population grow, the load is also constantly increasing. With heavier loads, the margins of the transmission lines will decrease and the stress level of the system will increase, thus increasing the risk of cascading blackouts. To lower the corresponding risk, there are various engineering responses to blackouts, either through upgrading and maintenance of the equipment such as transmission lines or by operational strategies such as improved dispatch and control. It has been conjectured in Carreras et al. and Dobson et al. [29, 30] that these opposing processes lead to a dynamic equilibrium that is self-organized critical.
- 6) External factors: Many external factors outside the power grid can also contribute to the initiation and propagation of cascading blackouts. If we only pay attention to the power grid itself, we may neglect important risks. For example, if the trees under some lines are not pruned or cleared

properly, it is possible that the lines can be tripped due to tree contact even when the lines are not overloaded, especially in very hot days with low wind [4]. Tree-caused outages are important on system reliability and can cause a large portion of preventable power outages in regions with trees [31–33]. The growing or falling into overhead lines of trees is generally regarded as the single largest cause of electric power outages [23]. Two significant outages in the western North America in 1996 [12], the U.S.-Canadian blackout on August 14, 2003 [13], and the outage in Italy on September 28, 2003 [14], can all be attributed to trees to some extent [23]. More generally, extreme weather can significantly increase outage rates and interacts with cascading effects [34]. Extreme space weather due to coronal mass ejections has the potential to damage the transformers and cause blackouts [35, 36]. Between 2003 and 2012, roughly 679 power outages, each affecting at least 50000 customers, occurred due to weather events [37]. The number of outages caused by severe weather is expected to rise as climate change increases the frequency and intensity of hurricanes, blizzards, floods, and other extreme weather conditions [38].

- 7) Emerging problems: The traditional power grid is undergoing a massive transformation across its entire spectrum – generation, transmission, and distribution – through the various smart grid initiatives. For example, it is increasingly dependent on its cyber infrastructure to support the numerous power system applications necessary to provide improved grid monitoring, protection, and control capabilities. Besides, high penetration of renewable generation can bring more risks due to the interactions between the grid and the renewables [20]. With the heavily integrated distributed energy resources, the power grid architecture is evolving fast from a utility-centric structure to a distributed smart grid [39]. These significant changes bring emerging problems and challenges to the modeling and understanding of cascading blackouts.
- 8) Difficulty in benchmarking and validation: In the last 20 years, many models, software tools, and analytical tools have been developed to study cascading blackouts. Benchmarking and validation are necessary to understand how closely a model corresponds to reality, what engineering conclusions may be drawn from a particular tool, and what improvements need to be made to the tool in order to reach valid conclusions [40]. However, because cascading blackouts are rare events and are usually very complex with several different mechanisms happening at the same time, it is very difficult to verify and validate each of these models or tools.

In Chapters 2 and 3 of this book, we will discuss various models that can be used to model cascading failures and to help understand why and how cascading blackouts happen, based on which effective mitigation measures can be developed to reduce the cascading risks.

1.2 Importance of Controlled System Separation

1.2.1 Mitigation of Cascading Failures

Catastrophic power blackouts can cause tremendous losses and influence up to tens of millions of people. The Northeast Blackout of 1965 was one of the first significant, widespread power outages of the world, causing the disruption of electricity supplies on November 9, 1965, in a huge area covering parts of eight northeast states in the United States and Ontario in Canada [11]. Since then, many efforts have been made to avoid blackouts in North America and other countries all over the world. However, large blackouts continue to happen. Some recent blackout events include the Northeast blackout on August 14, 2003 [13], and the Southwest blackout on September 8, 2011, in North America [41], the European blackout event on November 4, 2006 [42], and the Indian blackout events on July 30 and 31, 2012 [17].

In general, each historical blackout was the consequence of a long chain of cascading failures of individual components triggered by a variety of events such as concurrent multiple equipment failures, natural disasters, mistakes in operations, and so on. Once cascading failures initiate, they successively weaken the transmission network until inevitable system collapse and power outage over a large area [43]. Especially in a late stage of cascading failures, the time allowed for the grid control center to take system-level corrective actions is often very limited, a matter of a few minutes or tens of seconds. Therefore, automatic systemwide protection and control schemes are critical in mitigating cascading failures once failures start to propagate from a local area towards a wide area. At present, most of the existing protection systems lack systemwide coordination. They are either prone to trip equipment under potentially insecure conditions or designed in an event-based control mechanism to react when detecting any planned contingency. Thus, uncoordinated protective actions may not stop cascading failures; rather, they may even trip more equipment to exit operations, cause overload of some remaining equipment due to shifting of load, weaken the transmission network, and as a result, accelerate propagation of failures.

To mitigate cascading failures in a smart grid, it is necessary to develop more adaptive, systemwide control and protection schemes that can coordinate local protective relays to automatically execute an optimized control strategy in real time using wide-area measurements. In many power grids, widely dispersed synchrophasors such as phasor measurement units (PMUs) are important elements of smart grid technology applied to transmission systems. Synchrophasors provide GPS-synchronized real-time voltage and current phasor data at a high sampling rate (e.g., 30–60 Hz) comparable to or exceeding the AC system frequency and can be networked to construct a wide-area measurement system (WAMS) by means of advanced communication infrastructures. A WAMS enables the real-time monitoring of global dynamics of the whole power grid under

disturbances and can help coordinate protection and control actions at the system level. A framework for developing a WAMS-based protection and control scheme is suggested here for mitigation of cascading failures:

- 1) A comprehensive table of control strategies is designed based on adequate offline studies for a wide range of contingency scenarios and operating conditions.
- 2) The strategy table is maintained online and updated in a timely manner, for example, every 1–15 minutes, to cover any new appearing scenario or operating condition not addressed by offline studies.
- 3) Once the WAMS detects or reliably predicts any major instability, a control strategy that matches best the current situation from the table with adaptive refining should be performed in time.

1.2.2 Uncontrolled and Controlled System Separations

Consider an interconnected power system having multiple control areas. In general, tie lines connecting the control areas are more critical in power system operations than the other transmission lines because tie lines have relatively high voltage levels and transmission capacities and are key components constituting the backbone of the transmission network. The outage of any tie line causes the areas it connects to be more vulnerable to changes in operating conditions and disturbances. On one hand, the power flow originally carried by the opened tie line will be shifted to the lines on other transmission paths connecting the same two areas. These lines will have reduced power transfer margins. As a result, the transmission network will decrease its robustness and increase its risk to overload other lines. On the other hand, the trip of any tie line can energize power swings on electromechanical oscillation modes and increase the risk of rotor angle instability of the generators in the areas near the tripped tie line. Either line overloading or power swings may trigger protective actions. Local protective relays are seldom coordinated at the system level and are prone to be responsive to power swings, either stable or unstable, and as a result, that may cause unwanted trips of lines, transformers, or generators and even disconnect the transmission network into electrical islands. This is referred to as “uncontrolled system separation.”

Some unintentionally formed islands may have a high generation-load imbalance. Thus, maintaining the frequency and voltage levels of such islands must either shed a large amount of load in load-rich islands or trip many generators in generation-rich islands. Moreover, the group of generators isolated into an island may not easily keep synchronism and can lead to an out-of-step condition. Without effective control to synchronize and stabilize generators of the group, some of the generators will have to be tripped by out-of-step protection relays. Also, formation of islands can cause significant power-flow redistribution

in some islands and overloads of some lines or transformers, which will be tripped by further protective actions. Thus, line or transformer failures will continue to cause propagation of failures in those islands.

An effective protection and control measure called controlled system separation (CSS) is considered the final resort against a power blackout under cascading failures [44, 45]. It is also called controlled or intentional system islanding in some literature to distinguish it from uncontrolled system separation or islanding [46, 47].

When loss of integrity of the transmission network becomes unavoidable under cascading failures, rather than waiting for uncontrolled system separation to occur, the control center may proactively perform CSS by separating the power transmission system into electrical islands in a controlled manner so that each island is strategically formed with matched generation to stably support its load through a subsystem within the island. Thereafter, although the network loses its integrity, electricity continues to be supplied to most of customers of the system in parallel islands and thus a power blackout is effectively prevented. Once all failures are fixed, the whole system can be restored by resynchronization of all electrical islands. Such a resynchronization requires lower efforts and costs than a blackstart process since most of loads are saved. The latter has to restart the system in the blackout area following a long procedure including starting blackstart generation units to crank other nonblackstart units, energizing transmission lines and picking up loads, which usually takes several hours.

At present, CSS is not widely implemented by power industry. The power grids having schemes of CSS deployed are those experiencing a number of uncontrolled separation events in the past or considering uncontrolled separation as a major threat to grid operations under extreme weather conditions like storms or hurricanes. Typically, CSS schemes are designed based on out-of-step protection schemes with both tripping and blocking functions, which are traditionally applied to protect generators and power systems during unstable conditions [44]. The out-of-step tripping function can isolate unstable generators or control the separation of two areas going out of step, while the blocking function can block unnecessary actions of distance relay elements that are prone to operate during unstable power swings. Out-of-step protection schemes are mainly applied to individual generators or transmission corridors whose conditions are simple enough to detect from local measurements.

If highly reliable, fast, wide-area measuring and communication infrastructures are available in a smart grid, the existing out-of-step protection schemes can be upgraded and coordinated at multiple locations to implement more adaptive and effective CSS. The increasing deployment of synchrophasor-based WAMS in many countries enables the development and deployment of a practical WAMS-based CSS scheme in the near future based on upgraded out-of-step protection schemes. The WAMS can play critical

roles in performing CSS. For example, the WAMS can contribute the following to a CSS scheme:

- It helps operators monitor real-time electromechanical oscillations between control areas and identify the most vulnerable tie lines as potential separation points.
- The system dynamics authentically captured by the WAMS may help detect or predict out-of-step conditions with generators to identify the right timing to conduct CSS.
- Once electrical islands are formed after CSS, the WAMS can continuously monitor frequency and voltage excursions in each island and trigger necessary remedial actions to stabilize the subsystem in the island.
- All electrical islands can be resynchronized more easily to restore the whole system with the aid of synchrophasors placed in different islands.

Chapters 4 and 5 of this book will elaborate key questions about CSS and what useful techniques can be used to answer the questions. Specifically, an important problem of finding separation points for a power system is formulated based on the constraints on islands formed after CSS. Techniques that support WAMS-based online CSS will be introduced and integrated to establish a WAMS-based CSS scheme.

1.3 Constructing Restoration Strategies

1.3.1 Importance of System Restoration

Electric power systems, like transportation, communication, and gas systems, are among the most critical infrastructures of modern societies. These infrastructures share some common characteristics, such as wide geographical coverage, interconnection of numerous components, high reliability requirements, and so forth.

Power systems do have some defining features that contribute to the exceptional complexity of this type of artificial system. First, the generation and consumption of large amounts of electricity have to be implemented simultaneously. The imbalance between generation and consumption instantly causes disturbances between various components spanning a large geographical area. Second, the diversification of the interconnected components in power systems results in various nonlinear properties and dynamics under hybrid time scales. Third, uncertainties from the generation side (such as renewable energy sources), the customer side, and the exogenous factors (for example, extreme weather conditions) can constantly create disturbances that impact the security and reliability of a power supply. As such, power system operation and control are highly complicated. Some significant unforeseen disturbances may cause power systems collapse.

The history of major failures in power systems, namely total blackouts or widespread outages, is almost as long as that of the power industry itself [48]. Some major failures from the late 1970s to the year 2003 with high adverse impacts can be found in Adibi et al. [49, 50], among which the most severe one is the US-Canada blackout of August 14, 2003. In this catastrophic event, a greater than 60 GW load was interrupted for 50 hours. These outages have a huge adverse impact on the economy of modern societies. For example, the Electric Power Research Institute of the United States (EPRI, US) has estimated that US economic loss from outages has reached US\$104–164 billion per year [51]. Therefore, minimizing the duration of outages and their impact on the public has become a major concern of system operators.

After a power system collapses, power system restoration is a time-consuming and complicated process involving a series of control actions, taken by the system operators with rigorous temporal dependency, to rebuild the generation and transmission of the power supply and eventually to restore the interrupted electric supply to the affected customers. The studies in power system restoration aim to reduce the possibility and the impact of major outage events by providing solutions for restoration planning, real-time situation awareness, preventive controls, corrective controls, and restorative controls, in the context of restoration processes. After a major outage happens, system operators attempt to restore the power system back to a secure normal operating condition. The control actions may involve ascertaining the extent of outage, maintaining the stable operation of generating units with blackstart capability, cranking nonblackstart units, energizing transmission lines and transformers to establish cranking paths, picking up loads (i.e., restoring the electric supply to customers), and performing voltage and frequency control.

1.3.2 Classification of System Restoration Strategies

1.3.2.1 Diversification of Restoration Strategies

The effectiveness and efficiency of a restoration strategy after an outage depend primarily on the match of this strategy with both the characteristics and the post-fault state of the target power system.

On one hand, the portfolio of generating units will affect the restoration process substantially. According to the proportion of various types of generating units, the power systems can be categorized into thermal systems, hydrothermal systems, and primarily hydro systems [48]. For the thermal systems, the restoration process can be divided into four phases; namely, restarting steam units, reconnecting generation stations, picking up loads, and interconnecting islands. For the hydrothermal systems, the restoration process differs from thermal systems, in that the entire transmission network can be energized in one step. For primarily hydro systems, the restart of generating units is not a

major concern. Instead, the switching of long-distance high voltage transmission lines becomes the critical emphasis.

On the other hand, the restoration process should consider the actual outage scenarios. The restoration strategies considering diverse postdisturbance conditions can be grouped into the following five general philosophies [52]: build-upward, build-downward, build-inward, build-outward, and build-together. For example, for a total blackout, the build-upward can be applied to sectionalize the power system into islands, then to restore and firm up these islands, and eventually synchronize all of them. In situations where tie lines are available, the build-inward can be employed, in which some transmission lines are established with the aid of tie lines. Important stations can thus be restored and the restoration process can proceed.

1.3.2.2 General Restoration Phases

The diversification of restoration strategies causes difficulty in refining the general technical challenges and proposing systematic solutions to facilitate the restoration process. By surveying the comprehensive industry practice, associated manuals and guidelines, general restoration phases are proposed in Fink et al. [52]. These phases are termed preparation, system restoration (or network reconfiguration; to avoid ambiguity between system restoration and power system restoration, network reconfiguration will be used hereafter in this book to refer to the second phase), and load restoration, identifying the common features underlying various restoration processes. The major concern and measures taken in each phase are different from those in other phases.

In the preparation phase, the priority is to identify the system status and take action as quickly as possible. The initial energy sources – surviving generating units and those with blackstart capacity (hydro units, gas turbines, etc.) – are identified and are used to crank nonblackstart units. The critical loads, such as the offline power demand of nuclear generating units [53], are also to be restored. Necessary transmission switches will be conducted to establish paths from the surviving generating units to the nonblackstart units and critical loads. This phase typically lasts 1–2 hours.

In the network reconfiguration phase, the major objective is to reestablish the skeleton of the transmission network. Tasks that will be carried out include (i) energize key transmission lines and important substations, (ii) firm up islands and synchronize them as appropriate, and (iii) restore a small number of loads to stabilize generation and for voltage control. This phase typically lasts 1–3 hours.

In the load restoration phase, the goal is to restore service as quickly as reasonable to the interrupted customers based on the load importance/priority. In this final phase, the load pickup can be carried out in a larger increment since the generation and the transmission network have been firmed up in the previous phases. However, caution should be taken to limit the total load pickup

subject to the total available frequency response capacity. In addition, load pickup should not be done in a hasty fashion due to the uncertainty of the complicated load behaviors.

1.3.2.3 Reliability Guidelines and Standards for Restoration

To enhance reliability and impose critical general guidelines in the context of power system restoration, both North America and Europe have established formal documentation for the planning, drilling, and operation of restoration processes.

The European Network of Transmission System Operators for electricity (ENTSO-E) has drafted the network code on emergency control and restorative control for regional transmission networks [54], such as Baltic, Continental Europe, Britain, Nordic, and so on. This draft collects the existing rules and practice in various areas and identifies common practice and well-recognized critical issues. This draft also highlights the importance of wide-area system state assessment, information exchange among transmission system operators, and coordination among participants during the restoration process.

As a comparison, North America has established more rigorous restoration standards for utilities to follow. The Federal Energy Regulatory Commission (FERC) established the NERC for developing and enforcing reliability standards for power systems, in the context of planning, operation, emergency, and restoration [55–60]. The NERC standards related to power system restoration are as follows.

- 1) EOP-005-1: System Restoration Plans
- 2) EOP-005-2: System Restoration from Blackstart Resources
- 3) EOP-006-1: Reliability Coordination – System Restoration
- 4) EOP-006-2: System Restoration Coordination
- 5) EOP-007-0: Establish, Maintain, and Document a Regional Blackstart Capability Plan

The key information carried in these standards is outlined as follows.

- 1) The plans, procedures, and resources should be available to restore the power system on the occurrences of actual outage events.
- 2) The transmission operator's system should have adequate blackstart resources and reliable paths that reach the nonblackstart units. Personnel should regularly drill the procedures to start up the blackstart resources.
- 3) The control actions taken by various restoration participants must be coordinated to ensure reliability in each phase of restoration.
- 4) The regional blackstart capacity plan plays a central role in enabling sufficient blackstart capacity to function as expected, and therefore should be maintained and tested on a periodical basis.

1.3.2.4 Emerging Challenges and New Research Opportunities

Although the standards mentioned provide general guidelines during the restoration process, a wide spectrum of challenges needs to be solved. Besides the technical challenges summarized in Adibi et al. [48, 49], some new challenges, resulting from both the deregulation and growth of concern in modern resilient power systems, have created profound theoretical and practical questions. Moreover, new types of components, such as high-voltage direct-current (HVDC) transmission systems, provide new options in conducting the restoration process. These emerging requirements and new components have added new research dimensions to power system restoration. Furthermore, state-of-the-art optimization theory and high-performance computing technologies have permeated almost all engineering disciplines, including power system engineering. These advancements present powerful tools for modeling and solving mathematical problems arising from power system restoration. However, applying these theories and technologies is not a straightforward task.

1.3.3 Challenges of System Restoration

1.3.3.1 Restoration for Power Systems Under Market Environments

Whether the restructuring of the power industry contributes to the frequency of the major outage events is still an issue with diverse options. There seems to exist no strong evidence to relate the power market to the blackout risk [61]. However, under market environments, the operation of both the power system and the power plant is quite close to the reliability margin and therefore impacts the security of the power system [50].

Restoration in a market-based power system is far more complicated than in a vertically structured one. This is because the various independent restoration participants, such as transmission owners, distribution owners, and generation owners, have their own concerns and obligations, whereas the control actions taken by each party should be coordinated [62]. How to implement a smooth coordination during restoration is still an open question.

In addition to technical challenges, regulatory and economic issues in the restoration should also be taken into consideration [62, 63]. The blackstart service is commonly regarded as a type of ancillary service. The pricing of blackstart service and the blackstart cost are difficult to calculate, since the benefits are embedded in the entire restoration process and are distributed among collaborative yet independent entities. This difficulty adds barriers for market participants to invest in the blackstart capacity or associated technological innovation.

1.3.3.2 Resilience Requirements for Future Power Grids

Power systems have been experiencing a paradigm shift toward more reliable, sustainable, environmentally friendly, economic, and efficient modern power

grids [64]. The self-healing capability is the first defining feature of modern power grids [64, 65]. This capability is in essence the immune system of modern power grids that enables problematic elements of a power grid to be identified, isolated, and restored, with little or no manual intervention, such that the interruption of electric supply can be minimized [66].

To fulfill the goal of enabling a self-healing resilient power grid, the concept of “smart restoration” [51] has been proposed, with the key idea being that power grids are able to automatically perform self-assessment, response to disturbances, and conduct preventive/corrective/restorative control as necessary.

Designing and deploying such modern power grids is not an easy task. The following fundamental challenges must be met. First, the traditional restoration methodology based on offline planning together with operators’ experience must be changed. Emerging requirements include, but are not limited to, an advanced measurement system for situation awareness, efficient and reliable control methods based on rigorous computation to enable the online close-loop operation, and a reliable communication system that enables smooth coordinated controls. Second, owing to the growth of environmental concerns, renewable energy sources (RES) are playing an increasingly important role in the generation side. The percentage of RES capacity in the generation portfolio has reached such a point that RES cannot be neglected in any operation scenario. The uncertainty and variability of RES, however, will hinder the participation of RES in the restoration process, where security and reliability are crucial issues.

On the bright side, new types of power system components and advancement of control, optimization, and computation technologies provide powerful new tools to overcome these fundamental challenges.

1.3.3.3 Emerging Components and Novel Measurement Methods

There are ample new types of components and technological innovations that benefit the development of modern resilient power grids.

HVDC has been widely used in power systems [67], with the appealing feature of transferring a large amount power over a long distance in an economic and flexible fashion. Depending on the topologies and control methodologies, HVDC can be categorized into two types, the line commutated converter (LCC-HVDC) and the voltage source converter (VSC-HVDC).

LCC-HVDC is generally recognized as incapable of supplying a passive load; therefore, it has no blackstart capability. Yet recent research shows that this type of HVDC could serve as a blackstart source if novel control strategies are employed [68, 69]. By contrast, VSC-HVDC inherently has the capability as a blackstart source [70]. How to efficiently utilize HVDC links in different phases of restoration needs further studies.

On the generation side, thermal generating units are commonly regarded as lacking blackstart capability. Fortunately, the fast cut back function (FCB) may enable thermal generating units to have some blackstart capability within a

considerable period after a major outage happens. FCB function enables a unit in normal loading level to instantaneously reduce its output down to the house load level in a stabilized operation mode after it is tripped from the power system [71]. This is done by rapidly cutting back the fuel, feed water, and air in response to the turbine-generator output. By triggering this function, the running unit is always ready for parallel operation back to the power system. Thus, FCB capability will benefit power system restoration as a new option.

1.3.3.4 Advancement of Optimization and Computation Technologies

It is common practice that decision-making during power system restoration is modeled into various optimization models. The optimization models bridge the objective with the large spectrum of constraints that power system restoration must take into account.

One fundamental challenge in power system optimization is the convexification of power flow equations [72], such that the state-of-the-art global optimization algorithms can be applied to obtain the solution within polynomial time. This challenge is also important because the power system restoration must consider the power flow as constraints. If one applies numerical optimization algorithms to solve power-flow-constrained optimization models in power system restoration, the convexification of power flow equations is the critical step. However, it is still an open question, providing ample research opportunities. The other challenge is how to solve optimization models with integral and differential equations, which in nature reflect the power system dynamics. Generally, there is no analytical solution to this type of dynamic optimization model. The construction of an efficient algorithm is important to implement an online control for power system restoration. Both challenges will be addressed in this book.

As for high-performance computing technology, graphics processing units (GPUs) have been successfully applied in many engineering disciplines, including power systems [73, 74]. When applying GPUs in power system computations involving power flow, it is still unknown how to facilitate the sparse feature of the power system in the data-parallel computation paradigm, since GPUs are not designed to solve the sparse linear system with significant data dependency. This question will also be addressed in this book, particularly aiming to improve the efficiency of time-domain simulation for the load restoration strategies.

1.4 Overview of the Book

This book will, for the first time, provide a comprehensive introduction to power system control under cascading failures that covers all three major topics related to cascading failures in power transmission grids: (i) modeling and

understanding cascading failures (Chapters 2 and 3); (ii) mitigation of cascading failures by controlled system separation (Chapters 4 and 5); and (iii) power system restoration from cascading failures (Chapters 6–10). Related state-of-the-art technologies will be introduced and illustrated in detail with hands-on examples for the readers to learn how to use them to address specific problems. The following is a brief summary of the rest of the book.

Chapter 2 introduces typical models for the simulation of cascading failures, categorized into two classes. The first class of models is general cascading failure models, which are abstract and applicable to many complex systems, including power systems. They include the Bak–Tang–Wiesenfeld sandpile model, failure-tolerance sand-pile model, Motter–Lai model, influence model, binary-decision model, coupled map lattice model, CASCADE model, and interdependent failure model. The second class of models is specifically power system cascading failure models, developed for power system cascading blackouts. They include the hidden failure model, Manchester model, OPA model, and its variants and cascading failure models considering dynamics and detailed protections.

To understand cascading failures, Chapter 3 discusses several theories and models that can extract useful and actionable information from simulated or historical cascading failure data, answering why and how cascading failures happen in electric power grids. Specifically, this chapter focuses on analyses using the self-organized criticality theory, branching process model, multi-type branching process model, and failure interaction models considering dynamics and detailed protections.

Chapter 4 first introduces three important questions on CSS (controlled system separation): Where to separate? When to separate? How to separate? Then the chapter focuses on finding separation points for CSS. Constraints on separation points are presented in detail. The mathematical problems on separation points are formulated based on graph theory. Useful techniques for solving separation points, such as slow-coherency-based generator grouping, graph-theory-based power network reduction, and the ordered binary decision diagram method, are introduced. The three-step approach is suggested to integrate these techniques for checking constraints on separation points.

Chapter 5 first presents several techniques that enable an online CSS scheme using synchrophasor-based wide-area measurements. These techniques include measurement-based spectral analysis to determine a two-cut separation boundary by mode shapes, the “frequency-amplitude curve” to predict angular instability from drifting oscillation frequencies, a phase-locked loop-based method for accurate online identification of generation grouping, and an algorithm for real-time out-of-step prediction across a determined separation boundary. Then a unified framework for practical implementation of WAMS-based CSS is suggested to address the questions “where,” “when,” and “how.”

Chapter 6, as the first chapter on power system restoration, introduces the constraints to be addressed during a practical process of system restoration. The first set of constraints are general physical constraints on the startup procedures of generating units, system sectionalizing, and reconfiguration and load restoration, which concern most power systems. The second set of constraints are specifically about electromagnetic transient behaviors of a power system during restoration, such as the constraints on generator self-excitation, switching overvoltage issues with lines, resonant overvoltage issues and magnetizing currents with transformers, and voltage and frequency during the load picking up process.

Chapter 7 presents the methodology and implementation algorithms for optimization of a restoration strategy satisfying the constraints on both generation starting up and load restoration. The optimization of generation starting up is achieved under a bi-level framework by solving a primary problem minimize the duration of restarting generating units and establishing the network and a secondary problem determining the outputs of restarted generating units and picking up dispatchable loads. The optimization for load restoration is to formulate and solve a mixed-integer nonlinear load restoration problem.

Chapter 8 presents the optimal strategy of harnessing renewable and energy storage in power systems restoration. The optimization models and solution algorithms are introduced to address the uncertainty and variability of renewable energy resources in restoration planning. The operations and control of wind turbines are presented for blackstart and load restoration. The roles of energy storage (including pumped-storage hydro units, batteries, and electric vehicles) in alleviating uncertainties of renewables are discussed with the optimal coordination strategies.

Chapter 9 introduces emerging issues and related technologies for power system restoration. The emerging issues include considerations and applications of flexible alternating current transmission system (FACTS) and HVDC technologies during system restoration, applications of PMUs to facilitate the process of restoration, frequency deviations with load restoration and other reliability concerns during system restoration, and the dispatch of microgrids to speed up system restoration.

Finally, Chapter 10, from a system planning perspective, presents the methodology for assessment and optimization of the blackstart capability with a power system. A decision support tool is introduced to assist utility companies in planning studies on their blackstart capabilities.

This book is written as a reference for postgraduate students and researchers who work in the field of power system control under cascading failures. The book can also be used as a reference by electrical or system engineers to improve industry practices in power system planning and operations against cascading failures and blackouts.

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