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A Review on Cascading Failure Analysis for Integrated Power and Gas Systems

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***Abstract*—The increasing use of natural gas power generation has strengthened the interdependence between the power and natural gas subsystems in the integrated power and gas system (IPGS). Due to the interactions between the two subsystems, the disturbances in one system may spread to the other one, triggering a disruptive avalanche of subsequent failures in the IPGS. This paper presents a survey of cascading failure analysis for the IPGS. First, we identify the important features characterizing cascading dynamics in individual power and gas subsystems. Then, we will discuss the features for the cascading failure analysis in the IPGS and future research.**

Keywords—cascading failures, power flow, gas flow, dynamics, IPGS, modeling

I. INTRODUCTION

The natural gas power generation is increasingly used due to its low carbon emission and strong operation flexibility and high efficiency [1]. This intensifies the interaction and interdependencies of the power and gas subsystems in the integrated power and gas system (IPGS) and thus poses the challenges for the reliable and secure operation of the IPGS. A typical example is a widespread blackout in Texas on February 2021, where over half of the electricity supply came from natural gas. Due to the extreme winter weather, a sudden interruption of the gas supply occurred and natural gas power plants were subsequently shut down, leading to about 35.71% reduction of the power supply. Meanwhile, due to the shortage of reserve in the system, more than 25 million customers were eventually affected [2]. The coupling characteristics of the power and gas subsystems could cause the cascading failures in the IPGS. A local disturbance or failure triggered in one subsystem may propagate to the other subsystem through the energy coupling components, and the propagation of disturbance or failure even reflect back to the original subsystem results in severe cascading effects between the two subsystems [3]-[4]. Therefore, it is urgent to investigate the cascading failures in the IPGS.

In the literature, several works have analyzed the security and reliability of the IPGS considering the interdependency of power and gas subsystems such as those presented in [5]-[10]. In [5], the long-term IPGS reliability considering the power-to-gas devices and gas storages was evaluated utilizing Monte Carlo simulation. In [6], the short-term IPGS reliability was analyzed by the network equivalent and integrated optimal energy flow techniques. In [7], a multi-state model was proposed for the IPGS reliability assessment. In [8], a reliability assessment framework for the IPGS was proposed. In [9], the IPGS resilience under extreme events was evaluated using Monte Carlo simulation. In [10] , the reliability-based planning for the multiple energy hub in the IPGS was proposed based on minimal cut-maximal flow algorithm. However, the cascading failure effects were not considered in these works.

While there are many works on the cascading failure analysis in individual power system or gas system such as those summarized in [15]-[19], the cascading failure studies in the IPGS are limited [11]-[14]. The cascading failure propagation throughout the IPGS is different from that in individual power or gas system, due to distinct physical characteristics of power and natural gas systems. To understand the cascading dynamics in the IPGS, the paper first identifies the important cascading features characterizing cascading dynamics in individual power and gas systems. Then, we discuss the features for the cascading failure study in the IPGS and future research topics. The rest of this paper is organized as follows. Section II presents the overview of the key features for cascading failure study in power systems. Section III provides the overview of the important features for cascading failure analysis in gas systems. Section IV discusses the features for the cascading failure study for the IPGS with the existing works. Some conclusions and future perspectives are presented in Section V.

II. CASCADING FAILURE ANALYSIS IN POWER SYSTEMS

Cascading failures are one of the main mechanisms leading to widespread blackouts of the power system. In the literature, various models have been proposed to understand fault propagation and investigate effective mitigation strategies. In this section, the important features characterizing the cascading failures in the power system are discussed.

A. Power Flow Redistribution and Redispatching

The power flow redistribution and redispatching after component failures are important for the cascading failure analysis in the power system [47]. When one of the elements in the power system such as a transmission line fails, the system will redistribute the power flow of the failed component to nearby elements. If nearby elements do not have the capacity to handle the additional power flow, they have to shift some of their power to other nearby elements to balance generation and load in the system. Otherwise, the power system operator has to redispatch all the available generation units and loads to eliminate the power imbalance. If the adjustment of generation output cannot realize the system power balance, electric load shedding will be implemented by the system operator.

The power flow redistribution and redispatching are important in the cascading failures of the power systems. In the literature, the power flow redistribution and redispatching

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are considered in different models for the cascading failure analysis. Initially, the power flow redistribution is modeled using a topological approach since it is easy to outline the entire power system as a network [20]. However, this method cannot capture the operating conditions of a realistic power system. To address this issue, DC power flow was used to model cascading failures such as the OPA model, where the standard DC power flow equations are used to approximate the generator redispatch while keeping the power within restrictions [21]. DC power flow mainly considers the real power in the power system, but it ignores reactive power and voltage characteristics, which are needed for actual power system operation. To address the shortcoming, AC power flow was further used to model cascading failures in power systems to model the power flow redistribution and redispatch [22].

B. *Power System Dynamics and Stability*

A cascading failure is the uncontrolled and successive loss of parts of a power system, usually triggered by one or more disturbance events [23]. In addition to the power flow redistribution, the propagation of cascading failures is involved by power system dynamics and stability such as voltage stability, transient stability, small-signal stability, frequency stability, etc. These important features are discussed as follows.

1) Voltage Stability

Voltage stability analysis solves the steady-state power flow equations to determine voltage collapse margins. Voltage instability could cause the system collapse and even a blackout. The past outages have shown the significant role of voltage stability, such as during the 2003 blackout in the United States and Canada [24] or the 2009 blackout in Brazil [25]. To understand the impact of voltage stability on cascading outage propagation, several models have been created in the literature in [26]-[27].

2) Transient Stability

Transient stability analyzes the synchronization capability of the power system to withstand various faults. Based on the differential and algebraic equations, transient stability analysis is considered to be one of the most comprehensive and complex approaches for power system stability analysis. Transient stability analysis has been widely used in power system control design [28]. Several previous works have investigated the impact of transient stability on cascading failure analysis in the power system such as those presented in [29]-[31].

3) Small Signal Stability

Small signal stability analyzes the oscillation stability of the power system following small disturbances such as inter-area and intermachine oscillations. Although very few works focus on the impact of the small-signal stability on cascading failures, small-signal stability becomes a more and more important feature for the cascading failure analysis in the power system due to the increasing integration of renewable energy resources such as wind and solar through power electronic inverters. The inverter-based RERs (IB-RERs) provide expected real and reactive power based on their electronic controls, which link renewable energy resources to the power system. These controls may in turn depend on a stable reference signal from the power system. As the reference signal becomes less stable, inverter control dynamics become increasingly influential on overall system behavior, resulting in negative consequences to grid reliability such as system equipment damage, the loss of power generation, and power quality concerns, making the entire system less stable and potentially causing the system to collapse [32].

4) Frequency Stability

Frequency stability is the ability of the power system to maintain steady-state frequency, following a severe system upset, resulting in a significant imbalance between generation and load [33]. It depends on the ability to restore the equilibrium between system generation and load, with minimum loss of load. Frequency instability can cause a continuous frequency swing and will lead to the tripping of generating units or load. Various reasons can lead to loss of system frequency stability, such as the loss of generation which may result from a sudden imbalance between system generation and load demand [7]. In the literature, several works have proposed cascading models for investigating the impact of system frequency characteristics coupling with power flow redistribution, such as those presented in [34]-[35]. Particularly, the increasing IB-RER penetration, accompanied by retiring/displacement of synchronous generators has caused low-inertia operating conditions in the power system. Low-inertia power systems are likely to experience relatively large frequency variations following a generation/load mismatch. This is evidenced by a recently occurred event in the Australian National Electricity Market (NEM) grid, which led to cascading failures and electrical separation of the two states of Queensland and South Australia from the rest of the NEM [36].

5) Protection and Relay

In the power system, the function of protective relaying is to cause the prompt removal from service of an element of a power system when it starts to operate in any abnormal manner that might cause damage or otherwise interfere with the effective operation of the rest of the system. Power protection system plays an important role not only in possible triggering of the initial event, but also in further propagating the disturbances, leading to major blackouts. In [37]-[38], major Western Systems Coordinating Council (WSCC) events (the North Ridge earthquake, December 14, 1994, July 2 and 3, 1996, and August 10, 1996), involved either false trips of line protection relays or generator protection equipment. Hence, it is needed to study the hidden failures imbedded within the protection system. Hidden failures are the insecure or failed protection system that remains undetected until abnormal operating conditions are reached. In addition, system protection and controls coupling with system dynamic stability play important roles in blackout evolution. The cascading failure model with system protection has been proposed in the literature, such as [39]-[40].

III. Cascading Failure Analysis in Gas Systems

Cascading failures are also prominent in the gas system [41]. The gas system is an equally important part of the world infrastructure [45]. In the literature, various models have been proposed to understand how the failures propagate through the gas network and analyze when a failure could lead to a cascading failure. In this section, the important features characterizing the cascading failures in the gas system are discussed.

A. Gas Flow Redistribution and Redispatching

Similar to power flow redistribution and redistpatching in the power system for the cascading failure analysis, gas flow is redistributed and redispatched when there are failed elements such as gas pipelines in the gas system. The gas flow of the failed component is shifted to nearby elements. If nearby elements cannot handle the additional gas flow to balance gas production and gas load, the gas system operator needs to adjust gas production or shed gas load for the reliable operation of NGS. The gas flow redistribution and redispatching is important for the cascading failure analysis in the gas system [13],[44].

In the literature, the feature of gas flow redistribution is often ignored when the gas system is represented by a complex network model, where edges represent gas pipelines and nodes represent gas and transmission stations [46]. Thus, such a network model cannot capture the operating conditions of a gas system. To address this shortcoming, gas pressure and net gas supply are modeled in the gas system. When the net gas supply is positive, it corresponds to a supply of gas at that specific gas or transmission station. When the net gas supply is negative, it corresponds to the demand for natural gas at that specific gas or transmission station. This is referred to as the network flow balance constraint, which is set using the network flow balance equations and the Weymouth equation. Once this redistribution fails to meet the constraints set by the equations, a cascading failure begins [19].

B. Gas System Dynamics

Compared to power system dynamics, gas dynamics are mainly characterized by those in transient flow and link pack in the literature, which will be discussed as follows.

1) Transient Flow Dynamics

In the gas system, it takes time for gas to flow in the system from the supply to the load, which is a trivial matter for the cascading failure analysis. When a disturbance or a failure occurs in a gas system, the system takes a certain amount of time to recover from this disturbance to reach the initial steady-state value [13]. To model this feature, the principles of fluid dynamics and the detailed pipeline characteristics such as gas pressures are used to describe the gas flowing through a pipeline. To maintain the pressure levels of gas pipelines, the gas compressors with their constraints are modeled such as nodal pressure constraints, pipeline flow constraints, gas production constraints, and load curtailment constraints [42].

2) Line packs

Line packs describe the amount of gas contained within a given network. Increasing line packs in the gas system can improve system flexibility in operational reliability. The line pack is an important feature for the cascading failure analysis in the gas system. The transients in the link pack are modeled by the dynamic model of link packs, which solves the time-dependent flow equations used in a gas system [44]. Line packs can also be described by the steady-state model. This model is however not accurate as pipeline transients are ignored, especially when considering the fluid dynamics available in pipelines.

IV. Cascading Failure Analysis in IPGSs

In this section, the works existing in the literature are discussed according to the important features presented in Sections II and II to characterize cascading failures in power and gas systems. Also, the interdependency modeling between power and gas subsystems in the IPGS is discussed for the existing works.

A. Power and Gas Flow Redistribution

Work has been done to ensure the proper modeling of interdependencies in power and gas networks [48]. In the literature, there are limited works on the cascading failure study of the IPGS [11]-[14],[42]-[43]. In [11] and [12], the cascading failures in the real IPGS were analyzed based on a graph theory-based methodology. In [13], a novel reliability evaluation model of IPGSs considering the impact of cascading failures was built by employing the dynamic cascading analysis model and Monte Carlo simulation methods. In [14] and [42], a cascading failure model was presented to study the propagation of cascading failure caused by various contingencies, where the steady-state power flow and dynamic gas transmission were incorporated and combined together. In [43], a cascading failure simulation method coupling with a hybrid machine learning method was proposed for the cascading failure analysis of IPGSs.

The feature of redistribution and redisptaching of power and gas flow is considered in most of the existing works. Specifically, the power flow redistribution and redispatching are not included in [11] and [12] as the graph-based method is mainly used in the cascading failure study. However, the power flow redistribution and redipatching are considered in [13]-[14],[42]-[43]. Particularly, [14] and [43] use DC power flow to model the feature while [13] and [42] uses more accurate AC power flow to model it. Similar to the power flow redistribution and redispatching, the gas flow redistribution and redispatching are included in the models of references [13]-[14],[42]-[43] in addition to references [11] and [12].

In these existing works, only the work presented in [43] analyzed the impact of uncertain operating conditions (e.g., uncertain power and gas load levels, generator outputs, gas well supply, etc) on cascading failures of the IPGS. The impact is important for the cascading failure study of the IPGS because the uncertain operating conditions affect the power and gas redistribution and redispatching, which thus impact the cascading failure results. The uncertainty in operating conditions becomes more and more significant due to the increasing penetration of renewable resources such as wind and solar. Renewable generation is variable under uncertain weather conditions. In addition, the other soft factors, such as operating policies and human factors may increase the uncertainty in the planning and operation of the IPGS. Thus, including these uncertain impacts will be essential for future studies for the IPGS cascading failures.

B. Power and Gas System Dynamics

The feature of power and gas dynamics are not fully considered in the existing works [11]-[14],[42]-[43]. The gas dynamics are included in the models presented in [13]-[14] by transient gas flow modeling, but only [13] includes the feature of line pack in the cascading failure model. On the other hand, the power system dynamics and stability are not considered in these existing works. As discussed in Section II, the propagation of cascading failures is involved not only by the power flow redistribution and redispatching, but also by power system dynamic stability such as voltage stability, transient stability, small-signal stability, frequency stability, etc. Particularly, the increasing integration of IB-RERs into the electric power system through power electronic interface have caused low system inertia and low short-circuit capacity, which has challenged the safe and reliable operation of the modern power system. Incorporating the power system dynamic stability in the models for the cascading failure study of the IPGS is important to understand the failure propagation between the power and gas subsystems. Thus, how to incorporate power and gas system dynamics into the models for the cascading failure study of the IPGS are future research topics.

C. Power and Gas AI-based Analysis

Recently, machine learning methods have been widely used in various research disciplines. However, only the work presented in [43] has used machine learning techniques for the vulnerability analysis of IPGSs under uncertain initial states. In future research, it is valuable to use the existing big data and machine learning capabilities to extract actionable intelligence for cascading outage modeling, prediction, and mitigation as well as anomalous event detection. Also, it is useful to explore the dynamic interactions of IPGS components during the cascading failure process by machine learning techniques, which will be beneficial to the enhancements in IPGS resilience and understanding of anomalous event patterns and cascading outages, while reducing a high computational burden to perform power system dynamic assessment for cascading failure study of IPGS in online applications.

V. Conclusions

This paper reviews the current progress on the cascading failure analysis of the IPGS. First, various features characterizing cascading dynamics in individual power and gas systems were discussed. Then, we discussed the features for the cascading failure analysis in the IPGS with the existing works in the literature. Several interesting and important issues are still open, and possible directions for future research are highlighted as follows:

1) In the existing works on cascading failure analysis in the IPGS, the used models will need to further consider the impact of uncertain operating conditions on cascading failures of the IPGS. Due to the increasing integration of renewable resources into the power system, the uncertainty in IPGS operating conditions becomes more and more significant. The impact is important for the cascading failure study of the IPGS because the uncertain operating conditions affect the power and gas redistribution and redispatching, which thus impact the cascading failure results. In addition, the other soft factors, such as operating policies and human factors may increase the uncertainty in the planning and operation of the IPGS.

2) The existing works did not consider the power system dynamics and stability in cascading failure models of the IPGS. In the power subsystem, the propagation of cascading failures is involved not only by the power flow redistribution and redispatching, but also by power system dynamic stability. Moreover, power system dynamic instability issues also affect the cascading failure propagation in the gas subsystem due to the increasing interdependency between the two subsystems in the IPGs. Thus, in future research incorporating the power system dynamic stability in the model development for the cascading failure study of the IPGS is important to understand the failure propagation between the power and gas subsystems, so that the analysis results can be used for the technique development for preventing and mitigating cascading failures in the IPGS.

3) The existing works have limitations to the application of machine learning techniques in the cascading failure analysis of the IPGS. In future research, it is valuable to use the existing big data and machine learning capabilities to explore the dynamic interactions of IPGS components during the cascading failure process and extract actionable intelligence for cascading outage modeling, prediction, and mitigation as well as anomalous event detection. This will be beneficial to the enhancements in IPGS resilience and understanding of anomalous event patterns and cascading outages.

The authors sincerely hope that this survey paper can provide some insights and stimulate further exciting research to bridge academic researchers and practicing engineers toward further developments of risk-aware techniques for preventing and mitigating cascading failures in IPGS.

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