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Showcase #2

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

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Introduction

Natural gas power generation is increasingly used due to its low carbon emission and strong operation flexibility and high efficiency. This intensifies the interaction and interdependencies of the power and gas subsystems in the integrated power and gas system (IPGS) and thus poses challenges to the reliable and secure operation of the IPGS. The coupling characteristics of the power and gas subsystems could cause 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, resulting in a disruptive avalanche of subsequent failures in the IPGS. Therefore, it is urgent to investigate the cascading failures in the IPGS. While there are many works on the cascading failure analysis in the individual power system or gas system, the cascading failure studies in the IPGS are limited. The cascading failure propagation throughout the IPGS is different from that in individual power or gas system, due to the distinct physical characteristics of power and natural gas systems. To understand the cascading dynamics in the IPGS, we review the literature to identify the important features characterizing cascading dynamics in individual power and gas systems. On this basis, we discuss the features of the cascading failure study in the IPGS and future research topics.

Cascading Failure Analysis in Power Systems

In the literature, the following features are important for the cascading failure analysis in the power system.

- Power Flow Redistribution and Redispatching
    - The power flow redistribution and redispatching after component failures are important for the cascading failure analysis. 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. Initially, the power flow redistribution is modeled using a topological approach since it is easy to outline the entire power system as a network. 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, where the standard DC power flow equations are used to approximate the generator redispatching while keeping the power within restrictions. 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.
- Power System Dynamics and Stability
    - Voltage Stability: The 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.
    - Transient Stability: The transient stability analysis focuses on 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.

- Small Signal Stability: The small signal stability analysis is used to assess 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.
- 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. 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.
- 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 an abnormal manner that might cause damage or otherwise interfere with the effective operation of the rest of the system. The 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.

Cascading Failure Analysis in Gas Systems

In the literature, the following important features are considered for cascading failure analysis in the gas system

- Gas Flow Redistribution and Redispatching
    - 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. 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. 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.
- Gas System Dynamics
    - 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. 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.

- 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. 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.

Cascading Failure Analysis in Integrated Power and Gas Systems

The table below summarizes the current works on the important features investigated in cascading dynamics in individual power and gas systems as well as those in the IPGS:

Table 1. Features for cascading failures investigated in current works for individual power and gas systems and the IPGS

Investigated Features for Cascading Failure Analysis	Power System	Gas System	IPGS
Power Flow Redistribution and Redispatching	Yes		Yes
Voltage Stability	Yes		No
Transient Stability	Yes		No
Small Signal Stability	Yes		No
Frequency Stability	Yes		No
Protection and Relay	Yes		No
Gas Flow Redistribution and Redispatching		Yes	Yes
Transient Flow Dynamics		Yes	Yes
Transient Stability		Yes	Yes

Recommendations for Future Research

By reviewing various features in the current works on cascading failure analysis for individual power and gas systems as well as the IPGS, future potential research can be highlighted as follows:

1. The existing works did not consider the power system dynamics and stability in cascading failure models of the IPGS.
2. 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.
3. The existing works have limited 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.