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A cascading failure model based on AC optimal power flow: Case study

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HIGHLIGHTS

- AC-based cascading failure model (ACCF model) is applied to IEEE power grids.
- The ACCF model is proved feasible.
- Some failed lines are not close to initial faulty elements in cascading failure.
- Loss curves are symmetric when branch failure rates are low and high respectively.

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ABSTRACT

Simulating the grids cascading failure process is an essential means of preventing cascading failures. In traditional cascading failure models, DC power flow models are applied widely, but reactive power characteristic cannot be reflected. This study improves and applies an AC-based Cascading Failure model (called ACCF model), which captures bus load shedding and branch failures, all via AC power flow and optimal power flow analyses. Taking the IEEE 30- and 118-bus power systems as case studies, the ACCF model is proved feasible. With case studies, this study reveals that during the cascading failure, the broken branches are not necessarily close to the initial faulty elements, and some of the affected nodes/branches are "far" away from the initial faulty nodes. And as the initial branch failure probability increases, the system real power loss probability function gradually changes from approximate power distribution to a normal distribution. Meanwhile, the study also discovers that as the initial branch failure probability further increases, the system real power loss changes from a normal distribution to a distribution that appearing to be symmetric with the loss function under a low initial branch failure probability. The findings could facilitate grids safety and stable operation, as well as grids disaster prevention and relief.

1. Introduction

With the constant improvement of modernization level and the persistent advancement of intelligent power grids construction, large-scale electric power system interconnection has become an inexorable trend in countries around the world. However, interconnection of power grids is likely to result the power grids dynamic behavior become more

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complicated, make it more sensitive to the load characteristics and make the issue of steady state more severe. All these characteristics along with the even bigger network resulted from power grids interconnection make it more susceptible to electric power catastrophe caused by cascading failures. The major power failures occurred in recent years also makes people more deeply recognize the necessity and urgency of preventing power grids cascading failure and damages caused thereby [1–3].

Building a cascading failure model is an important method for having an in-depth comprehension of grids operation pattern, preventing cascading failures, minimizing cascading failure range and damage and ensuring infrastructure system safety. At present, there are two types of models simulating grids cascading failures: complex network-based cascading failure models [4–6] and approximate dynamic behavior-based cascading failure models [7].

Complex network-based cascading failure models mainly include betweenness-based model [8], M-L model [9,10], dynamical redistribution model [11,12], cluster distribution model [13,14], CASCADE model, Branching process model [15], HOT (Highly Optimized Tolerance) model [16,17], etc. Complex network-based cascading failure model has such advantages as easy solution, few parameter inputs, high-efficiency, etc. However, these algorithms generally give large-extent approximate treatment and assumptions of the power grids. For example, betweenness-based model would assume that electric energy flow between any two nodes via the shortest path. M-L algorithm also has similar assumptions, and the model utilizes the total number of the shortest paths that passing through the node to define the node load. However the above assumptions usually have certain differences from actual power grids, thus, errors are inevitable with complex network-based cascading failure model, and as a result it is not easy to apply them to physical power grids.

Relatively speaking, approximate dynamic behavior-based cascading failure models simulate actual grids operation process as far as possible, of which the widely applied models mainly include OPA model [18], hidden failure model [19], (DC) optimal power flow cascading failure model, Manchester model [20–22], etc. An innovation of OPA model is that it divides the cascading failure development process into slow dynamic process and quick dynamic process, of which the slow dynamic process forecasts the load increase and system reliability improvement, etc. Starting with one power flow solution, the quick dynamic process utilizes Monte Carlo method to generate an initial failure on a random basis, and once there is a branch break, it would optimize the power flow distribution based on the DC power flow model. An advantage of this model is that it considers both slow dynamic and quick dynamic processes, which is more agreeable with the reality. Similar to OPA model, hidden model also uses Monte Carlo method to simulate initial failure of the line, and uses DC flow model to simulate the interlocked tripping process triggered off by covert fault under protection. Though these DC-based models are used widely, they also have come certain deficiencies. For example, reactive power characteristics cannot be reflected by DC-based models. Manchester model utilizes AC model to avoid the demerits of DC flow models. The model utilizes AC flow model and gives a comprehensive consideration to the various factors relevant to cascading failure development, including cascade and sympathetic tripping of transmission branches, heuristic representation of generator instability, under-frequency load shedding, post-contingency re-dispatch of active and reactive resources, and emergency load shedding to prevent a complete system blackout caused by a voltage collapse. However, the power flow solution process of Manchester model has not considered the economic dispatch of operation, and neither given a full consideration to the regulating function of the generator.

In order to simulate cascading failure occurring process more objectively, the authors have introduced an OPF (Optimal Power Flow) model to improve the AC flow model in Manchester model contained in Ref [23], and have built an ACCF (AC-based Cascading Failure) model. The ACCF model can give a reasonable consideration to economic dispatch, and the result achieved is more aligned with the actual grids operation norm.

On the basis of the ACCF model [23], here the authors introduce a constrained non-linear optimization method to help solving the ACOPF problem. Then the ACCF model is applied to the power grids by taking IEEE 30 and 118-bus systems as examples, in order to investigate the power grids cascading failure characteristics. Grids cascading failure characteristics as well as power loss distribution characteristics are studied under different failure quantities and failure probabilities of nodes and branches in the grid. In this manuscript, a node here denotes a substation or power station, and a branch denotes the electric line between two nodes. Research results of this paper can provide a basis for prevention of grids cascading failures and disaster prevention and reduction management of the power grids.

2. AC-based cascading failure model

The main process of ACCF model is as such: firstly, assume some of the nodes in the system are failed according to a certain principle; remove the failed nodes out of the system; determine new system status based on AC power flow and optimal power flow calculation results, and cut off part of the load when necessary; meanwhile, according to the power flow calculation result, if a steady state cannot still not be reached by cutting off part of the load, the model will then break the overload branch, and then recalculate the power flow distribution. Repeat the foregoing process, until the system reaches a new balance or the system splits into a number of isolated islands while a new balance is maintained within each island, finally evaluate the load loss resulted from the cascading failure. A basic introduction of this model is given below: