Analysis of Power System Vulnerability Considering Multiple Disturbances Corresponding to Information and Physics

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Abstract. With the continuous development of smart grid, the automation degree of power system continues to improve. The number of measurement-calculating and decision-controlling units of the power grid has greatly increased, and the scale of the power information network has become larger and larger. The stable operation of the power system is inseparable from the real-time dispatch of its information system. As the key infrastructure, power system has a huge impact on national security, economic development and social stability, and has become one of the key targets of terrorist destruction. In view of the fact that information network and power network integrate with each other currently, this paper focus on the functions of the power control center, modeling information systems together with physical systems. Considering that the power system has suffered multiple disturbances corresponding to information and physics, the quantitative analysis method is used to simulate the dynamic evolution process after the accident, and the loss of load is used as the evaluation index to analyze the vulnerability of the power system, to find the vulnerable components of the power grid. So effective protection measures can be taken to reduce the loss of the power system after this type of destruction. The constructed model is solved by mixed integer nonlinear programming method. IEEE Reliability Test System-24 verifies the feasibility and effectiveness of this model.

1. Introduction

The smart grid is a composite system composed of a virtual information network and a physical entity network, which is characterized by close coordination between the information system and the physical system [1]. The information system collects the operational data of the power system and sends it to the power control center for analysis. The power control center makes real-time decisions and controls the power system to ensure the safe and stable operation. At present, international terrorism threats, military conflicts and other unstable factors appear frequently. Power system as a hub for mutual transformation of various energy [2], is a key infrastructure of the country and has a tremendous impact on national security, economic development, and social stability. It has become the focus of destruction [3].

The current destruction methods toward the power grid are mainly divided into two types: the first one is to damage the primary equipment of the power system directly [4], mainly for the deliberate destruction of generators, substations, transmission lines, nodes and even some important loads. This type of destruction will cause one or more power equipment to exit running, thus changing the
topology of the power network, affecting the transmission and distribution of power seriously, and may even cause grid disassociation and chain fault, causing wide range of power cut. Another type of destruction is that terrorists use advanced network technologies to invade the power information network and destroy the functions of the information system [5]. Since the control and coordination of the physical equipment largely depend on the information system, the destruction on the information system may lead to a complicated physical interaction process and threaten the security of the power system ultimately. Reference [6] puts forward a new standard for the power systems vulnerability analysis in response to the physical damage caused by natural disasters and malicious destruction, and proposes how to formulate emergency treatment plans so that the grid can restore stable operation as soon as possible. Reference [7] defines information destruction in power systems, classifies information destruction from different perspectives, and analyses some typical scenarios. Reference [8] shows that injecting bad data into information systems deliberately can lead to control center making wrong decisions, which can not only interfere with the safe operation of the power grid, but also enable the terrorists to obtain illegitimate benefits. Reference [9] simulates destruction against information systems, causing the power system to lose security and stability directly, and proposes corresponding security defense measures. At present, most of the references consider the impact of a single destruction way on the power system, and do not model and analyze the physical system together with the information system. Compared with physical destruction, information destruction has the characteristics of low cost and concealment [10], and the damage to the power system may be more serious. Due to the information system is tightly coupled to the physical system, problems in any one system may lead to serious accidents.

This paper considers the interaction between information systems and physical systems, and considers that the power system has suffered physical destruction, thus some primary equipment of the power system was destroyed and exited operation. At the same time, if the power system suffered information destruction, the function of the power control center is invalid, so the generator output and load of each node of the power grid cannot be adjusted optimally. If the power system did not suffer information destruction, the control center can adjust the generator output and load optimally, with the goal of minimizing the load loss of the power system. Based on the topology analysis algorithm, this paper proposes a DC power flow method, which analyses the dynamic evolution process of power system accident quantitatively, and uses the load loss as the evaluation index of the accident after the disturbances related to information and physics. Finding the vulnerable components of the grid by establishing an analytical model of power grid vulnerability, effective protection measures can be taken to reduce the loss of the power system. The constructed model is solved by mixed integer nonlinear programming method. IEEE Reliability Test System-24 verifies the feasibility and effectiveness of this model.

2. Principles of power system vulnerability analysis

2.1 Dynamic evolution and simulation of power system suffering from disturbances related to information and physics

After the power system is destroyed, if the short-term transient process can be neglected, only concern about power system’s steady state after the accident, the power system steady state method can be used to analyse problems [11]. The dynamic evolution process can be described as: when some primary equipment (generators, transformers, power lines, etc.) are physically destroyed and then exit operation, causing changes in the topology of the power grid, further causing problems such as power flow transfer, branch power limit and power imbalance. If the information system is destroyed at the same time, it is considered that the power control center loses the optimal adjustment function. The relay protection device will cut off the overrun branch. At this point, the topology of the power grid will change again, causing a series of cascading faults. If the information system is not destroyed, the power control center optimizes with the goal of minimizing the load loss, and adjusts from the power supply and the load synergistically to ensure the power balance of the power grid while eliminating the
power over limit, thus avoiding the occurrence of cascading fault. The above dynamic evolution process is simulated using the steps of Figure 1:

Figure 1. The simulation steps of power system disturbances.
The description of Figure 1 is as follows:
(1) Set the components operating status. Set grid components exit operation which being destroyed.
(2) Power system topology analysis. Through topology analysis, obtain the number of disconnected
power islands (subsystems) after the grid is destroyed and obtain the power, network and load of each
power island.
(3) Perform the following analysis for each power island (subsystem) which includes both the
generator and the electrical load:
(3.1) Simulate power flow distribution. Firstly, proportional adjustment of power to ensure power
balance. Then calculate power flow to determine whether there is a branch overload, if yes, enter (3.2),
and otherwise enter (4).
(3.2) Judge the cascading fault. If the control center is invalid, it loses operational capability. All
overloaded branches are disconnected, then enter (3.3); if the control center is valid, it has operational
and control capabilities. The control center eliminates the overload of the branch according to the
strategy of minimizing the loss of the island load, and then enters (4).
(3.3) Subsystem topology analysis. It is concluded that the power island is further decomposed into
several unconnected new power islands (new subsystems) due to cascading fault, and obtain the power,
network and load of each new power island.
(4) Judge whether each power island (subsystem) containing the generator and the power load is
calculated, if yes, enter (5), otherwise return (3).
(5) For each new power island (new subsystem) containing the generator and load, re-simulate the
power flow distribution, cascading fault judgment and subsystem topology analysis until there is no
cascading fault (no new power islands appear).
(6) Judge whether each new power island (new subsystem) containing the generator and the power
load is calculated, if yes, enter (7), otherwise return (5).
(7) Statistics of total load loss.

The above vulnerability analysis problem considers that terrorists launch a destruction related to
information and physics on the power system, to achieve the purpose of destroying the power supply.
According to this method, the load loss of each power island can be obtained, and the total load loss is
used as the vulnerability assessment index of the power system. The damaged components, which
cause the most load loss, are the vulnerable components of the power grid and need to be protected.

2.2 Planning model for power system vulnerability analysis
First, define the variable of availability of the power control center:
\[ \eta = \begin{cases} 
1 & \text{Control center is valid} \\
0 & \text{Control center is not valid} 
\end{cases} \quad (1) \]

In (1), \( \eta \) represents the availability of the control center. Element 1 means the control center works
normally and element 0 means the control center loses its function.

● Objective function
This planning problem is based on the generators, power lines, substations and bus nodes as the
target of destruction in the power system. The decision variable is the generator output and load power
of each node under the control of the control center (if the corresponding node is controllable); the
objective is to minimize the total load loss:
\[ \text{Object} = \min \{ P_G, P_L \} \sum_{i \in I} \Delta P_{Li} \quad (2) \]

In equation (2): \( P_G, P_L \) represent the decision variable controlled by the system operator, which is
the vector expression of the generator's active output and load power of each node, and its dimension is
equal to the total number of nodes of the grid. \( \Delta P_{Li} \) is the amount of loss of load \( i \).

● Constraints
After the components of power grid are physically damaged, taking into account the action of the relay protection device to cause the damaged components to exit the operation, the constraints of the power system topology changes are as follows:

\[
\begin{align*}
\delta_{\text{Gen}}^j, \delta_{\text{Line}}^l, \delta_{\text{Bus}}^n, \delta_{\text{Sub}}^s & \in \{0, 1\} \\
\end{align*}
\]  

(3)

\[
\begin{align*}
Y_l = & \left(1 - \delta_{\text{Line}}^l\right) \left(1 - \delta_{\text{Bus}}^o(l)\right) \left(1 - \delta_{\text{Bus}}^d(l)\right) \\
Y_l & \prod_{s \in L_{\text{Sub}}^s} \left(1 - \delta_{\text{Sub}}^s\right) \prod_{l' \in L_{\text{Par}}^l} \left(1 - \delta_{\text{Line}}^{l'}\right) \\
H_j = & \left(1 - \delta_{\text{Gen}}^j\right) \left(1 - \delta_{\text{Bus}}^n(j)\right) \\
H_j & \in \{0, 1\}
\end{align*}
\]  

(4)

(5)

In equation (3), \(\delta_{\text{Gen}}, \delta_{\text{Line}}, \delta_{\text{Bus}}, \delta_{\text{Sub}}\) are vectors representing the functional state of the generators, power lines, nodes, and substations respectively in the power system. The vector dimension is respectively equal to the number of generators, power lines, nodes, and substations. Element 1 represents the fault of the power component without being destroyed. In equations (4) and (5), \(Y, H\) are vectors representing the availability of power lines and generators under the influence of the topology of the power system. The vector dimension is equal to the number of power lines and generators. Element 0 represents the component is not available and Element 1 represents the component is available. Equation (4) means that the power line \(l\) is not available when the following conditions occur: the power line \(l\) is destroyed, or the first node or last node of the power line \(l\) is destroyed, or the substations connected to the power line \(l\) is destroyed, and if the power line \(l\) is one of the multiple lines of the same pole, the multiple lines of the same pole will generally exit operation together after destruction. \(Y_l\) is the availability of power line \(l\). \(\delta_{\text{Bus}}^o(l)\) and \(\delta_{\text{Bus}}^d(l)\) respectively are the functional states of the first node and last nodes connected to the power line \(l\), all of which are 0-1 variables; \(L_{\text{Sub}}^s\) is a set of power lines connected to the substation \(s\), \(L_{\text{Par}}^l\) is a set of other power lines running on the same pole with the power line \(l\). Equation (5) means that the generator \(j\) is not available when the following conditions occur: the generator \(j\) is destroyed or the node connected to the generator \(j\) is destroyed. \(H_j\) means the availability of the generator \(j\), and \(\delta_{\text{Bus}}^n(j)\) means the functional state of the node connected to generator \(j\), all of which are 0-1 variables.

The equality constraints:

\[
P_G - P_L = B\theta
\]  

(6)

Equation (6) is the DC power flow equation [12]. \(P_G\) is a vector representing the generator active power of each node, \(P_L\) is a vector representing the load active power of each node, \(B\) is the DC power flow susceptance matrix, and \(\theta\) is a vector representing the node phase angle.
\[ P_l = Y_l \cdot X_l \cdot \sum_{n \in N} A_{ln} \cdot \theta_n \quad \forall l \in D \quad (7) \]

Equation (7) is the power flow equation of the power lines. \( P_l \) is the active power of the power line \( l \), \( X_l \) is the reactance of the power line \( l \), \( A_{ln} \) is the element of the line-node correlation matrix, \( \theta_n \) is the phase angle of the node \( n \), \( N \) is a set of system nodes, \( D \) is a set of power lines \( \sum_{n \in N} \sum_{j \in G_n} \left( P_{Gj} + \eta \cdot \Delta P_{Gj} \right) = \sum_{n \in N} \sum_{i \in L_n} \left( P_{Li} + \eta \cdot \Delta P_{Li} \right) \quad (8) \)

Equation (8) is the power balance equation. \( P_{Gj} \) is the active output of generator \( j \), \( \Delta P_{Gj} \) is the active power adjustment amount of generator \( j \) under the control of control center, \( G_n \) is the set of all generators which connect to node \( n \); \( P_{Li} \) is the active power of load \( i \), \( \Delta P_{Li} \) is the power loss of load \( i \), \( L_n \) is the set of all loads which connect to node \( n \) in the system.

\[ -Y_l \cdot P_{l \text{max}} \leq P_l \leq Y_l \cdot P_{l \text{max}} \quad \forall l \in D \quad (9) \]

\[ H_j \cdot P_{Gj \text{min}} \leq P_{Gj} + \eta \cdot \Delta P_{Gj} \leq H_j \cdot P_{Gj \text{max}} \quad \forall n \in N, \forall j \in G_n \quad (10) \]

\[ 0 \leq \Delta P_{Li} \leq P_{Li} \quad \forall i \in L \quad (11) \]

Formula (9) represents the power limits of power lines, and \( P_{l \text{max}} \) is the upper limit of the active power transmission value of the power line \( l \). Formula (10) represents the active power output limits of the generator \( j \). \( P_{Gj \text{max}} \) and \( P_{Gj \text{min}} \) are the upper and lower limits of the active power output of the generator \( j \). Formula (11) is the active power loss constraint of load \( i \), and \( L \) is the set of all loads in the system.

3. Case analysis

3.1 IEEE reliability test system-24(RTS-24) analysis

To verify the effectiveness of the proposed model, a simulated destruction was performed on the IEEE RTS-24. Its network structure shown as Figure 2:
3.1.1 Vulnerability analysis of power system under multiple disturbances of information and physics

First, simulating information destruction on power system, so the control center function is invalid. Then sample the primary equipment and simulate physical damage. The load loss and its proportion of the total load under each destruction scheme (the total load is 2850 MW) shown in Table 1:

Table 1. The load loss under different destruction schemes.

| Scheme number | Damaged components | Loss of load(MW) | Load loss ratio (%) |
|---------------|--------------------|------------------|---------------------|
| 1             | Lines:16-19,20-23A,20-23B | 309              | 10.84               |
| 2             | Lines:11-13,12-13,12-23,14-16,15-24 | 1086             | 38.11               |
| 3             | Node:13; Lines:7-8,12-23,16-17,15-21A,15-21B,20-23A,20-23B | 1638             | 57.47               |
| 4             | Nodes:13,15,18; Lines:12-23,16-17,20-23A,20-23B | 2257             | 79.19               |
| 5             | Nodes:2,13,15,18; Lines:12-23,16-17,20-23A,20-23B | 2378             | 83.44               |
| 6             | Nodes:2,13,15,16,18; Lines:7-8,12-23,20-23A,20-23B | 2533             | 88.88               |
| 7             | Nodes:2,7,13,15,16,18; Lines:12-23,20-23A,20-23B | 2658             | 93.26               |

It can be seen from Table 1 that when the ratio of load loss reaches 70% or more, nodes 13, 15 and 18 appear as destruction targets, which are vulnerable nodes of the grid. Lines 12-23 and double-circuit lines 20-23 almost in all destruction schemes, lines 7-8 and 16-17 also appear more often, which are vulnerable branches of the grid. Regardless of the destruction scheme, the vulnerable nodes and branches of the power grid are essentially unchanged. Through the above analysis, the security...
protection of these nodes and branches should be strengthened to reduce the loss of power system when it is destroyed.

3.1.2 Comparison of the load loss under two types of destruction
Select destruction schemes 2 and 4 in Table 1. Under the premise that the control center is valid and the control center is invalid, simulate physical destruction on the power grid and compare the load loss, as shown in Table 2:

| Scheme number | Damaged components | Loss of load (MW) |
|---------------|-------------------|------------------|
|               |                   | Control center  |
|               |                   | invalid | valid |
| 2             | Lines:11-13,12-13,12-23,14-16,15-24 | 1086 | 853 |
| 4             | Nodes:13,15,18; Lines:12-23,16-17,20-23A,20-23B | 2257 | 2022 |

It can be seen from Table 2 that for the same destruction scheme, the load loss is significantly reduced under the optimal adjustment of the control center, so the control center is also the important target that needs to be protected. In the process of power restoration, the control center should first be restored to normal operation in order to minimize loss.

4. Conclusion
Based on the background of high integration of information system and physical system, this paper proposes a vulnerability analysis model of power system subjected to disturbances related to information and physics, and solves this kind of problem by mixed integer nonlinear programming method. The loss of load is used as the evaluation index to analyse the vulnerability of the power system. Applying the model to analyse different destruction schemes, it can effectively find the vulnerable nodes and branches, and the corresponding protective measures can be taken to reduce the loss and improve the operational safety of power system.

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