Research of Complex System Theory Application on Reliability Analysis of Network System

Huang Jinyong
Reliability Data Centre
Electronic product reliability and environment testing, CEPREI
Guangzhou, CHINA
hjy_nuaa@hotmail.com

Feng Yankuan and Zhang Sandi
Reliability Data Centre
Electronic product reliability and environment testing, CEPREI
Guangzhou, CHINA
hjy_nuaa@hotmail.com

Abstract—Based on the analysis of the relation between complex system and complex network system, this article discusses the application of complex system theory on the reliability indexes confirmation, failure definition, reliability analysis, and reliability simulation validation of complex network system. This article proposes that it needs to consider the complex network’s characteristic and development rule, and research the underlying relation between the hypostasis of complex network system and reliability during the reliability research of complex network system.

Keywords—complex system; complex network; reliability; information entropy

I. INTRODUCTION

Complex network system is closely related to complex system. Complex network system can be regarded as a Complex system when corresponds its node to the agent of complex system. In fact, a great of Complex networks systems can be viewed as complex systems [1][2][3][4].

Complex network system reliability has been extensive and in-depth studied and the studies have achieved many important results in recent years. For example, survivability, availability and performability have been applied as reliability evaluation indexes for communication network system. Reliability evaluation methods such as application efficacy coefficient, fuzzy theory and neural network have been proposed also. However, the basic methodology of these studies is largely confined to the reliability theory of the single device. The methodology abstracts the network to nodes and links which can deliver a certain amount of information.

From the definition of reliability, we can see that the reliability of the system is the fundamental attribute of the system. The current reliability research of complex network system is not from the system point of view to reveal the potential relationship between the system inherent nature and the reliability of complexity network system. This is what hinders the reliability research of the current complex network system radically.

This article discusses the complex system theory application on reliability research of complex network by analyzing the relationship between of complex network system and complex system in order to play a forward role for reliability research of the complex network system.

II. RESEARCH OF THE RELATIONSHIP BETWEEN COMPLEX SYSTEM AND COMPLEX NETWORK SYSTEM

Complex system science has become a hot topic of people's attention in recent years, especially after the founder of Santa Fe Institute George. Cowan in the United States put the issue upgraded to 21st century scientific, people's interest is fueled in role.

Complex system is a system which has the characteristic of complexity. For example, it has a large number of interactive elements, complex and uncertain internal relation and its overall behavior is nonlinear. These characteristic can’t be reform by the system local variables and characteristics, and the speciality of entire system can’t be described by the system local characteristics formally or abstractly. Complex system has the characteristic of emergence, large scale, complexity of system structure, hierarchy and interactive / relational [5].

Figure 1. Structure diagram of complex system

Complex network system as one part of the complex system, it has all the common property of complex system. For example, interactive relationship between behavior and structure of complex network system is: when failure occurs, the associated routing and topology will change. And the change of routing and topology will affect the rate of failure
and flow of task in turn. They meet the interactive features as the complex system described above. The relationship between complex system and complex network system is shown in Figure 2.

![Figure 2. Relationship between complex system and complex network system](image)

Studying the complex network system reliability leaving the complex system theory is often one-sided. For example, some scholars propose to use probability and graph theory to describe the reliability of the network, but failed to describe out the relationship between behavior and structure of network system. So only using probability to analyze the occurrence of failure belongs to the traditional reliability, and only using the graph theory to consider the network topology and its change, namely, research of network survivability, is only available at its shape but not its quality.

III. APPLICATIONS OF COMPLEX SYSTEMS THEORY IN THE STUDY OF NETWORK RELIABILITY

A. Complex Network System Reliability Index System

Complex network system is part of complex system, having the general characteristics of complex system. Analyzing system reliability, we must proceed from its hypostasis. Reliability, which defined as in the time and certain conditions, the ability to complete the function, is the representation of capability. This representation is formed based on the structure, behavior and management/process control of the system itself. Some scholars put forward for a particular network system reliability index from the application point of view. Such as military communication networks, which measure reliability according to invulnerability and survivability of the network, as communication networks, which measure reliability according to performability of the network, or as electricity network system, which also measure reliability according to invulnerability and survivability of the network. The reliability indexes proposed above are for specific application fields. However, for general complex network systems, we need to find their common characteristics from where we start to consider reliability in a general complex network system. Through the relationship analysis between complex network systems and complex system, we can see that complex network systems consist of behavior, structure and management control. Therefore, reliability can be measured from these three aspects.

To analyze the reliability of complex network systems need to consider the following aspects:

1) **Complex network system behavior description** (probability + topology).
2) **Complex network system interaction** (probability + topology + control management).
3) **Complex network system function structure** (topology + control management).
4) **Complex network system fault propagation** (probability + topology + control management).

The biggest difference between complex network system and the general equipment in reliability is characteristics of dynamic, interactive and propagation. Therefore applying reliability theory of general equipment to analyze the reliability of complex network is out of the hypostasis of complex systems. Here we proposed the complex network system reliability index system as figure 3 based on the discussion above.

![Figure 3. Complex network system reliability index system](image)


B. Complex Network System Failures Definition

A complex network system is that consisting of nodes and links, and the relationships (such as interaction) between nodes, links, and environment are set up through the information flow, logistics, energy flow, finance flow, human resource flow etc. Its environment is a system environment, and its behavior is a system behavior, and its function is a system function. Its relationship flow set is a collection of system architecture.

For any system, there are inherent relationship and development rule between environment, structure and behavior or function. So there are inherent relationship and development rule between complex network’s environment, structure (in other words, the complex network flow set, including information flow, logistics, energy flow, capital flow, human resource flow), behavior and function [6].

Failure definition of complex network system is an important aspect. So far, it has not yet formed a unified opinion. In general, complex network system’s failure can be divided into topology fault and performance failures.

Topology structure fault means that there are not routing between two nodes because of the failure of node or link.

Performance failure is that the network can not provide a normal communication services from the user point of view.

From the point of topology structure, the network has $2^m$ states, $m$ is the total number of links and nodes. From the point of network performance, the performance status of network is different from that of other time. Although some scholars have proposed that a certain standard can be developed to determine the current network’s performance value or other value whether exceeds the standard value, but in different environment (common, military, real-time data requirements, data reliability requirements, etc.), the network can tolerate a different threshold.

For instance, figure 4 is a network. In figure, there are two clients, named S1 and S2, a server, named T, P1-P5 denotes the switch or router, and No 1 ~ 8 denotes links. Task 1 means that the data flow transmit from client 1 to server T, and we assumption that 1-3-7 as a priority routing for this task. When the data on link 3 beyond the link’s load, it will automatically select the link 5 to transmit data, while the link 3 continues working at this time, but it works on the state of full load.

Much of the communication network reliability analysis methods are based on the composition diagram of the node or link carrying a certain amount of information flow at present. There is one problem for these methods that all the data flow of task1 may go through from link 3, but task 2. Because link 3 has been occupied by task 1, there is no free link bandwidth for task 2. The data flow of task 2 chooses the link 5 for transmission finally. If we can say that the link 3 is congestion for task 2, so the network is fault for task 2?

Complex network system failures, has been detached from the device-level fault. From the point of complex system theory, the failures of complex network system are on the top level of equipment failures, and it not only related with equipment failures, but also with the control and behavior. Equipment failure just is one predisposing factor of complex system failures.

![Network data flow route](image-url)

Figure 4. Network data flow route

C. Complex Network Systems Reliability Analysis

1) Apply Renormalization Theory and Percolation for Complex Network Reliability Analysis

The theory of renormalization was proposed by KG Wilson, 1974[1]. It is useful for complex network reliability analysis. For example, whether the complex network works reliability when some nodes have fault, and it’s the network flexibility problem also.

The procedure that using the theory of renormalization for complex network reliability analysis is [1]: The thin constituting by metal and dielectric has many small cases, and the case is possessed by the variable $p$, which represents different probability. When $p$ increases to critical value $p_c$, the thin just become conductor. And then we can use the theory of renormalization to calculate the value of $p_c$. The procedure of renormalization is like Figure 5.

In Figure 5, the lowest row denotes that four cases are possessed by metal, and the second row denotes renormalization, and the first row denotes that the thin becomes one case through renormalization.

When the cases are possessed by metal both length and breadth, it has metal after renormalization. If two or fewer than two case are possessed by metal, it has no metal after renormalization.

We assumption that the metal possesses the case by the probability $p$, so all the four cases are possessed is $p^4$. In additional, the probability of three cases are possessed is $4p^3(1- p)$. So the probability of more than two cases are possessed by metal, represents by $p'$, is:

$$p' = p^4 + 4p^3(1- p)$$
So we can calculate the critical value $p_c$ by function 1:

$$p_c = p_c^4 + 4p_c^3 (1 - p_c)$$

The result of $p_c$ is 0.768, and this value close to the experimental value 0.752.

The method proposed above is useful for complex network reliability analysis. For example, we can apply renormalization to predigest the structure of network, and count the network critical value of the network fail with that.

The maximum entropy principle is that any water flow has the same probability to choose which path to go through, and the flux of the path is equality. So the risk of any path is fail which bring system in the situation of uncertainty is lesser, and the reliability is maximum.

Relative entropy model denotes that the maximum path entropy is relative to the water distribution network topology, and the maximum entropy represents the potential maximum reliability of system. So we defines relative entropy is the relative value of actual path entropy and maximum path entropy:

$$E_j = S_j / S_j^{\text{max}} \quad (0 \leq E_j \leq 1)$$

Where $E_j$ represents the relative path entropy of node $j$, $S_j$ is the actual path entropy of node $j$, $S_j^{\text{max}}$ represents the maximum path entropy of node $j$, when the network has only one path, the relative path entropy is 0.

The water distribution network system has 159 segment pipe, and 104 nodes, and the total water flux is 11948t per hour.

2) Application of Entropy Theory for Complex Network Reliability Analysis

It is found out that the network structure observably affects the transmit, exceed seep, class join dynamics, traffic and information flow, synchronization and control of chaos, Ising Model, XY critical Model, diffuse and response of quanta, boolean dynamics etc, and these affect network structure also[1].

So the information flow dynamics of complex network is an important issue now, and it is useful for understanding of telecommunication network’s information dynamics character, telecommunication network topology structure, prevent against for information congestion, network reliability and so on. And the research result of network has demonstration that the information flow of energy spectrum of internet has fractal structure, and long-time pertinence, and the congestion just as a result of network topology itself, not the fail of any server.

Tadic and her team have discovered that the www network has the characteristic long-time pertinence, and congestion problem just because package in the hub-nodes of network waits for long time to transmit [7][8]. Here an example of reliability analysis for water distribution network systems is proposed based on information flow dynamics and entropy theory.

First, we assumption that:

- We defines that path entropy is the measurement for water uncertainty of choosing path, and the water just chooses the path which has minimal resistance. So the path entropy just essentially denotes that the uncertainty is a result of different resistance, and the path entropy reflects the performance of the water distribution network systems.

- The maximum entropy principle is that any water flow has the same probability to choose which path to go through, and the flux of the path is equality. So the risk of any path is fail which bring system in the situation of uncertainty is lesser, and the reliability is maximum.

- Relative entropy model denotes that the maximum path entropy is relative to the water distribution network topology, and the maximum entropy represents the potential maximum reliability of system. So we defines relative entropy is the relative value of actual path entropy and maximum path entropy:

$$E_j = S_j / S_j^{\text{max}} \quad (0 \leq E_j \leq 1)$$

Where $E_j$ represents the relative path entropy of node $j$, $S_j$ is the actual path entropy of node $j$, $S_j^{\text{max}}$ represents the maximum path entropy of node $j$, when the network has only one path, the relative path entropy is 0.

- The water distribution network system has 159 segment pipe, and 104 nodes, and the total water flux is 11948t per hour.

Using the tool EPANET2.0 to build the water distribution network system simulation model and calculating the relative
path entropy of nodes and system by function (3) and protracting contour line, the result is like Figure 6. We can calculate the system relative entropy and the value is 0.686726, and the result tell us the system has to improve. The result becomes 0.721666 after improvement, here we using the way of adding a pipe, Figure 7.

Because complex network system is part of complex system, its primary characteristic is evolvement, self-government, and emergence. Most of network reliability simulation researches are limited on the performance and function simulation, and doesn’t consider the point of complex network system’s hypostasis. We propose that forecast simulation, forecast design, the worst situation analysis works should be the key for complex network simulation.

IV. CONCLUSIONS

Complex network system is part of complex system, and it has the characteristic of complex system. Based on the analysis of the relation between complex system and complex network system, this article discusses the application of complex system theory on the reliability indexes confirmation, failure definition, reliability analysis, and reliability simulation validation of complex network system. This article proposes that it needs to consider the complex network’s characteristic and development rule, and research the underlying relation between the hypostasis of complex network system and reliability during the reliability research of complex network system. It is an effective method for complex network reliability analysis, and needs more hard work for this.

REFERENCES