International Journal of Hybrid Information Technology
Vol.8, No.10 (2015), pp.115-128
http://dx.doi.org/10.14257/ijhit.2015.8.10.11

Reliability Analysis of Relay Protection Based on the Fuzzy-Markov Model

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Abstract

Relay protection and safety device are regarded as the sentry of safe and reliable operation of the power grid. It plays a very important role in the power grid, and can determine whether the normal operation of the power system. This article considers the influence of the fuzzy uncertainty of relay protection failure rate to power system on the basis of Markov model, and researches the dynamic fault tree analysis method in the case of fuzzy failure parameter. A dynamic fault model has been built. The triangular fuzzy numbers are used to express the failure rate of the components and system, after which the fuzzy Markov model has been established based on the dynamic fault tree model obtained before. The fuzzy reliability curve and fuzzy failure probability on given degree of membership could be obtained. Finally, the fuzzy Markov model based dynamic fault tree analysis method is used for reliability modeling and analysis of relay protection. The results show that this method can conduct reliability modeling and quantitative assessment effectively for systems which have dynamic failure characteristics and uncertainty of failure rate.

Keyword: *relay protection, dynamic fault tree, fuzzy Markov, uncertainty*

1. Introduction

At present, the analytic method is widely used in reliability assessment, Such as the Markov space conversion method [1, 2] and the fault tree analysis method [3, 4] *etc*. They have different strengths. The Markov model [1, 5] is a state space method which is commonly used. Since the model is a kind of global state space model, the computation of which would happen state explosion with the system scale growth. Therefore to adopt this method is not desirable directly. Traditional fault tree analysis (FTA) method is an effective tool for system reliability analysis. But in the reality, failure systems often have dynamic characteristics, and the traditional FTA as an analysis method of static logic or static failure mechanism is unable to describe the dynamic behavior based on system failure.

Aiming at the drawbacks of fault tree analysis method, some scholars have put forward the hybrid method combining analytical method and simulation method. Rao [6] presents a simulation method based on Monte Carlo, the method can be used for failure distribution under non exponential distribution case, and can also handle the dynamic logic gate in a cascade. Bobbio [8, 9] puts forward a kind of method based on Bayesian network to simplify the process of solving the dynamic fault tree. In most system reliability analysis process, which relay protection is in normal work or failure state is regarded as the certainty. In other word, it is sure that the probability of relay protection is in both two states. But the engineering system is not always certain in practice. Owing to various factors, the state and probability of relay protection system are often fuzzy. The above several analytical methods have not considered the fuzzy uncertainty problems in

ISSN: 1738-9968 IJHIT

the system.

In order to solve simultaneously these two problems of dynamic feature and fuzzy uncertainty in the systems, this chapter presents a dynamic fault tree analysis method based on fuzzy Markov model. The dynamic fault tree establishes the reliability model of system. Triangular fuzzy numbers describe the fuzzy probability of the bottom events, and describe the transfer rate between states in Markov model. The membership function of fuzzy failure probability on the fault tree top event is calculated by extension principle and parameter programming method of fuzzy numbers. Finally, the correctness and effectiveness of the method are verified through an example.

2. Dynamic Fault Tree Analysis Method

2.1 The Dynamic Logic Gate

One of the main disadvantages of the conventional fault tree analysis method is not modeled on the order of correlation in the system. In order to solve this problem, Dugan [10-12] proposed a new method for reliability analysis—Dynamic fault tree analysis. The method introduces a series of dynamic logic gates to describe the failure behavior of the system on timing rules and dynamic. These four kinds of typical dynamic logic gate mainly include Sequence Enforcing Gate (SEQ), Functional Dependency Gate (FDEP), Priority-AND Gate (PAND) and Spare gate (SP) *etc*.

(1) Sequence Enforcing Gate (SEQ)

SEQ has n input events, only when all events occur with the order from 1 to n sequence, the output event occurs. As shown in Figure 1 (a).

(2) Functional Dependency Gate (FDEP)

When the trigger event T occurs and causes events A, B to occur, the top event happens. Or any of the basic events A, B alone occurs, the top event also occurs. As shown in Figure 1 (b).

(3) Priority-AND gate (PAND)

When the basic events occur as the order from left to right, the output occurs. For example, the two inputs A and B, when A firstly occurred before B, the output of system occurs. Therefore the PAND is a special case of the SEQ as when the number of the bottom events is two. As shown in Figure 1 (c).

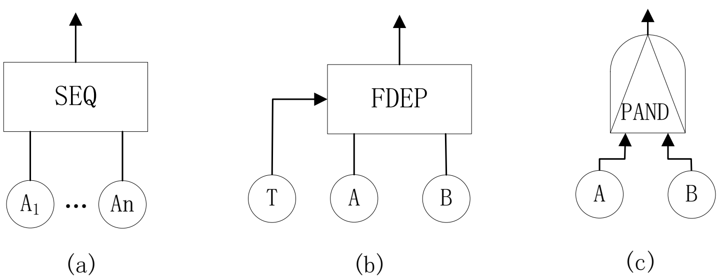

Figure 1. The Dynamic Logic Gate (a) Sequence Enforcing Gate (b) Functional Dependency Gate (c) Priority-AND Gate

There are usually a main input and one or a plurality of backup inputs in Spare gate (SP), spare parts and the main parts have the same function and failure rate. According to the different failure mechanisms, spare parts can be divided into three categories: Cold Spare gate (CSP), Cold Spare gate (CSP), Warm Spare gate (WSP), Hot Spare gate (HSP). The graphic symbols as shown in Figure 2.

(4) Cold Spare gate (CSP), if the main part A is in normal operation, the cold spare parts S will not run. Only the main part A fails, and the cold spare parts S also fails, the

top event would occur.

(5) Warm Spare gate (WSP), when the main part to work normally, warm spares in preparatory work state, when the main part and the warm standby parts are failure, the top event occurs. But the failure rate is very low.

(6) Hot Spare gate (HSP), hot spare S and main parts A also are all in working state, similar to the parallel. S could not be the only one. Only all of the parts fail, the top event will occur.

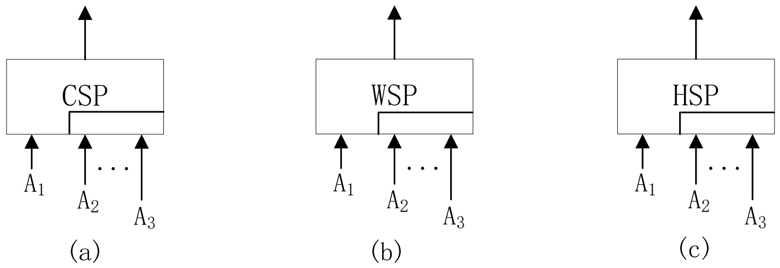

Figure 2. Three Kinds of Spare Parts of the Door (a) Cold Spare Gate; (b) Warm Spare Gate; (c) Hot Spare Gate

2.2 The Markov Model

In the dynamic fault tree, the occurrence probability of the sequence cut sets contains not only with combinations of events related, but also with order of the basic event occurs. Thus, the Markov model is used to simulate the process of failure and evaluate the reliability of the dynamic system.

Assuming that T is an infinite set of real numbers, if every and $X(t)$ is a random variable, $\{X(t), t\in T\}$ will be called random process. When a random process satisfies the following conditional probability relation, the random process is called a Markov process.

$$\begin{aligned}&P\left\{X(t_n)=x_n \middle| X(t_1)=x_1, X(t_2)=x_2,\cdots, X(t_{n-1})=x_{n-1}\right\}\\&=P\left\{X(t_n)=x_n \middle| X(t_{n-1})=x_{n-1}\right\}\end{aligned} \quad (1)$$

Where $x_i \in S$, S is the state space of the stochastic process, and $t_1 < t_2 < \cdots t_{n-1} < t_n$.

Pattern (1) reflects that Markov process has no memory, it is expressed that random process at probability of in depends only on the state of which has nothing to do with the previous time state. Under normal circumstances, the state space and the time parameter of Markov process can be discrete or continuous. Markov chain is the Markov process whose time and state are the discrete.

In a dynamic system, the failure process of the system can be described as the Markov process.

Assume that the system has n state $s_i(i=1,2,\cdots,n)$, the failure process of the system is described by Markov process $\{S(t), t\geq 0\}$. Where $s_i \in H$, the H is the state space Markov process.

The transfer rate of the state i and state j is expressed by $\lambda_{i,j}$, The failure process of the system can be described by the state transition diagram as shown in Figure 3.

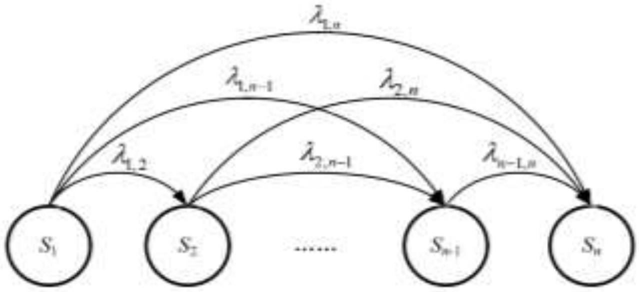

Figure 3. The State Transition of Markov Model Diagram

In Figure 3, s_1 represents that the system is in good condition; from s_2 to s_{n-1} represent the intermediate states of system failure process; s_n being the system failure state.

Assume $p_i(t)$ is the probability of every state s_i during t of the system, where $i = 1, 2, \cdots, n$. The differential equations of the above Markov model correspond to the following:

$$\begin{cases} \dfrac{dp_1(t)}{dt} = -p_1(t)\sum_{j=1}^{n}\lambda_{1,j} \\ \dfrac{dp_i(t)}{dt} = \sum_{j=1}^{i-1} p_j(t)\lambda_{1,j} - \sum_{j=i+1}^{n} p_i(t)\lambda_{i,j} \text{ , } \quad 1 < i < n, t \geq 0 \\ \dfrac{dp_n(t)}{dt} = -\sum_{j=1}^{n-1} p_j(t)\lambda_{j,n} \end{cases} \qquad (2)$$

The initial conditions of the model being: $\begin{cases} p_1(0) = 1 \\ p_i(0) = 0 (i = 1, 2, \cdots, n) \end{cases}$

To solve the above model can get the probability $p_n(t)$ of n states, which corresponds to the probability of top event of the fault tree, it is failure probability of the system in t time.

2.3 Dynamic Fault Tree Conversion to Markov Model

As the fault tree includes one or more dynamic logic gates, the fault tree is called dynamic fault tree. According to the graphical advantage of the Markov model, the dynamic logic gate converts to the Markov model, which can effectively solve the problem of solving the dynamic logic gate. The combination state of the dynamic logic gate input event used as the basic state of the Markov model, at the same time, the state transition probability of Markov model is set as a fault probability of input event, which can convert dynamic logic gate for the Markov model. The following will introduce how some typical dynamic logic gates are converted to Markov model.

(1) PAND: The two input PAND is converted into the Markov model as shown in Figure 4.

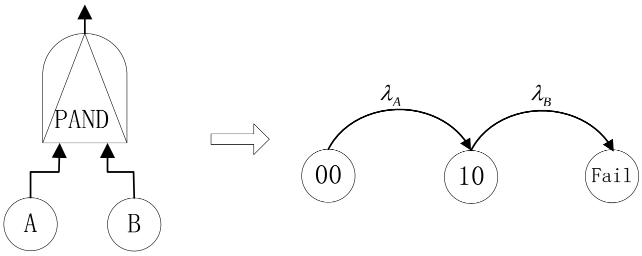

Figure4 the PAND Converted into the Markov Model

In Figure 4, "00" represents that the two parts A and B are in the normal state; "10 "represents that part A is failure, but part B is normal; "Fail" represents top event occurs, the system fails. λ_A and λ_B respectively represent failure rates of A and B, correspond to these two transfer rate in the Figure.

(2) FDEP: FDEP is converted into the Markov model as shown in Figure 5. λ_A and λ_B respectively represent failure rate of input parts A and B, λ_T is the failure rate of the triggering event. "000" for the three parts are all in the normal state of the system; "001" for the only part B of the system fails; "010" for the only part A of the system fails; "Fail" for the system fails. As shown in Figure 5 the transfer between states.

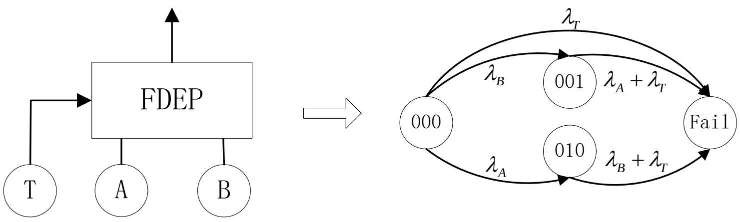

Figure 5. the FDEP Converted into the Markov Model

(3) SEQ: Like the previous two kinds of dynamic logic gate, The λ_i represents the failure rate of sequential input event A_i. The process of SEQ into Markov model is shown in Figure 6. The meaning of its every state is similar to the one before in Markov model.

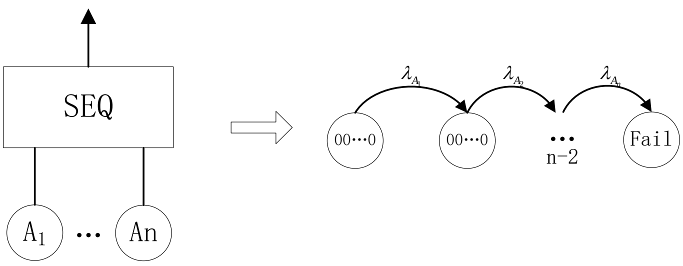

Figure 6. The SEQ Converted into the Markov Model

(4) Spare gate: As shown in Figure 7, CSP, WSP and HSP are converted into Markov model. Which A being the basic input, S being the space. λ_A and λ_S respectively express the failure rate of the operating state of A and S, The meaning of every state is same with the Markov model of the PAND (two input) in the state. According to the failure mechanism of all three kinds of spare gates, the space of the WSP also has a

certain failure rate before the basic input failure, which expressed as $\lambda_s^{'}$, and also $\lambda_s^{'} < \lambda_s$. When A fails, S will be fully working, and $\lambda_s^{'} = \lambda_s$. For the HSP, the spare S is always in working state, so $\lambda_s^{'} = \lambda_s$.

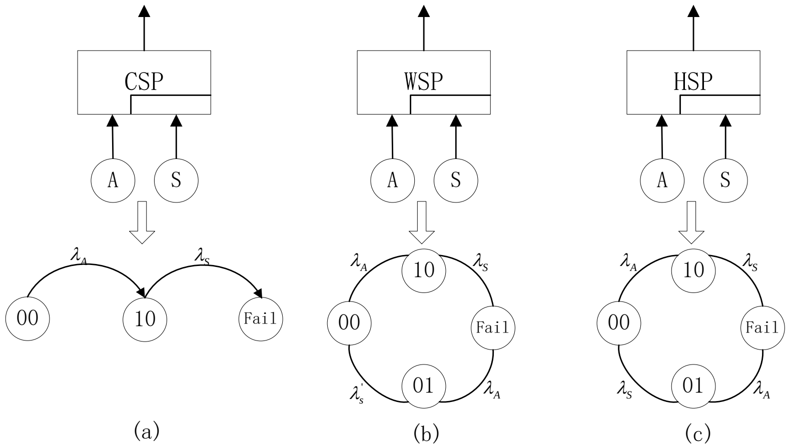

Figure 7. The Space Gate Converted into the Markov Model (a) the CSP converted into the Markov Model (b) the WSP Converted into the Markov Model (c) the HSP Converted into the Markov Model

3. The basic Concept of the Fuzzy Sets and the Extension Principle

3.1 The Fuzzy Set

In the reliability evaluation of complex engineering system, there are two kinds of uncertainty, random uncertainty and epistemic uncertainty. Zadeh proposed a system of mathematical theory (fuzzy set theory) to handle a kind of cognitive uncertainty in practice—Fuzzy uncertainty.

Given a set $\tilde{A}$ on the Universe U, for any $u \in U$, a real number $\mu_{\tilde{A}}(u) \in [0,1]$ which correspond to u, which determines the membership degree of a set $\tilde{A}$ of elements u. Set $\tilde{A}$ is called fuzzy set, $\mu_{\tilde{A}}(u)$ is called the membership of the fuzzy set $\tilde{A}$ corresponding to the element u. This mapping can be expressed as follows:

$$\begin{aligned} &\mu_{\tilde{A}} : U \to [0,1] \\ &u| \to \mu_{\tilde{A}}(u) \end{aligned} \tag{3}$$

For the fuzzy set $\tilde{A}$, if it is normal and convex fuzzy sets, it is called the fuzzy number. Triangular fuzzy number, the normal fuzzy number and trapezoid fuzzy number are the most common fuzzy numbers.

The typical triangular fuzzy numbers defined by its membership functions, as shown in formula (4):

$$\mu_{\tilde{A}} = \begin{cases} \dfrac{x-a}{b-a}, a \le x \le b \\ 1 \quad , x = b \\ \dfrac{x-c}{b-c}, b \le x \le c \\ 0 \quad , \text{others} \end{cases} \tag{4}$$

The graph expression of typical triangular fuzzy number is shown in Figure 8.

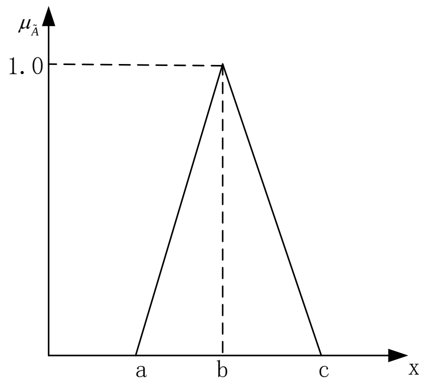

Figure 8. The Membership Function of Triangular Fuzzy Number

3.2 The Extension Principle

Zadeh proposes the concept of fuzzy set and fuzzy numbers to express and quantify the fuzzy information. In addition, Zadeh also proposes that the extension principle defines the fuzzy operation among fuzzy numbers.

In a series of fuzzy number $\tilde{X}_i$ on the Universe R_i given, $x_i \in R_i$ is the corresponding variable of the universe R_i and fuzzy number $\tilde{X}_i$. They is a variable in real number field R. $f(x_1, x_2, \cdots, x_n)$ is a mapping from variables x_i to variables y. We can use the mapping $f(x_1, x_2, \cdots, x_n)$ to induce a new fuzzy number $\tilde{Y}$ with the aid of fuzzy number $\tilde{X}_i$. Which $i = 1, 2, \cdots, n$. The extension principle can obtain the membership functions of it are as follows:

$$u_{\tilde{Y}}(y) = \sup_{\substack{x_i \in R_i (i=1,2,\cdots,n) \\ y = f(x_1, x_2, \cdots, x_n)}} \min(u_{\tilde{X}_1}(x_1), u_{\tilde{X}_2}(x_2), \cdots u_{\tilde{X}_n}(x_n)) \tag{5}$$

According to the extension principle, cut set Interval of the Fuzzy number is as follows:

$$\tilde{Y}_\alpha(y) = [\min_{1 \le i \le n} f(x; \mu_{\tilde{X}_i}(x_i) \ge \alpha), \max_{1 \le i \le n} f(x; \mu_{\tilde{X}_i}(x_i) \ge \alpha)] \tag{6}$$

So, to solve the lower and upper bounds of the fuzzy number can be transformed into a programming problem which solves a set of parameters. Parameter programming is constructed as follows:

$$\begin{array}{ll} \tilde{Y}_\alpha^L = \min f(x_1, x_2, \cdots, x_n) & \tilde{Y}_\alpha^U = \max f(x_1, x_2, \cdots, x_n) \\ \text{subject to } \tilde{x}_{1\alpha}^L \le x_1 \le \tilde{x}_{1\alpha}^U & \text{subject to } \tilde{x}_{1\alpha}^L \le x_1 \le \tilde{x}_{1\alpha}^U \\ \tilde{x}_{2\alpha}^L \le x_2 \le \tilde{x}_{2\alpha}^U & \tilde{x}_{2\alpha}^L \le x_2 \le \tilde{x}_{2\alpha}^U \\ \vdots & \vdots \\ \tilde{x}_{n\alpha}^L \le x_n \le \tilde{x}_{n\alpha}^U & \tilde{x}_{n\alpha}^L \le x_n \le \tilde{x}_{n\alpha}^U \end{array} \tag{7,8}$$

According to the above extension principle, interval boundary can be easily obtained in different cut set of fuzzy number.

4. Dynamic Fault Tree based on Fuzzy Markov Model

Combined with the Markov model and the fuzzy set theory, it is presented a new method for reliability analysis—dynamic fuzzy fault tree analysis method to analyze and model the reliability of the system with the dynamic failure and fuzzy uncertainty.

In this method, the dynamic fault tree model of the system is established according to the failure analysis of the system, and then the dynamic fault tree is converted into the Markov model. In the transformed of the Markov model, the fuzzy number represents the transitions rate among states, thus transition rate matrix of the model state becomes fuzzy state transition rate matrix. The form is as follows:

$$\tilde{A} = (\tilde{\lambda}_{i,j}) = \begin{pmatrix} \tilde{\lambda}_{1,1} & \tilde{\lambda}_{1,2} & \cdots & \tilde{\lambda}_{1,n} \\ \tilde{\lambda}_{2,1} & \tilde{\lambda}_{2,2} & \cdots & \tilde{\lambda}_{2,n} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{\lambda}_{n,1} & \tilde{\lambda}_{n,2} & \cdots & \tilde{\lambda}_{n,n} \end{pmatrix} \quad (9)$$

The fuzzy state transition process is shown in Figure 3.

So, the Markov model corresponding to differential equations which is formed by the fuzzy transition rate is following:

$$\begin{cases} \dfrac{d\tilde{p}_1(t)}{dt} = -\tilde{p}_1(t)\sum_{j=1}^{n}\tilde{\lambda}_{1,j} \\ \dfrac{d\tilde{p}_i(t)}{dt} = \sum_{j=1}^{i-1}\tilde{p}_j(t)\lambda_{1,j} - \sum_{j=i+1}^{n}\tilde{p}_i(t)\lambda_{i,j}\,, \quad 1 < i < n, t \geq 0 \\ \dfrac{d\tilde{p}_n(t)}{dt} = -\sum_{j=1}^{n-1}\tilde{p}_j(t)\tilde{\lambda}_{j,n} \end{cases} \quad (10)$$

Using the initial conditions $\tilde{p}_1(0) = 1$ and $\tilde{p}_i(0) = 0 (i \neq 1)$ to transform the above equations by means of Laplace-Stieltjes, The linear equation group obtained is as follows:

$$\begin{cases} s\tilde{p}_1(s) - 1 = -\tilde{p}_1(s)\sum_{i=2}^{n}\tilde{\lambda}_{1,i} \\ s\tilde{p}_i(s) = \sum_{j=1}^{i-1}\tilde{p}_j(s)\tilde{\lambda}_{j,i} - \sum_{j=i+1}^{n}\tilde{p}_i(s)\tilde{\lambda}_{i,j}\,, \quad 1 < i < n \\ s\tilde{p}_n(s) = \sum_{j=1}^{n-1}\tilde{p}_j(s)\tilde{\lambda}_{j,n} \end{cases} \quad (11)$$

To solve the above equations, the functions on are obtained, then it is to inverse Laplace-Stieltjes transform, the probability distribution of the system state on the time comes out in the end. The Upper and lower bounds of the fuzzy number can be obtained by the extension principle, namely the fuzzy failure probability of system.

5. The Example Analysis

According to the constitution and characteristics of the relay protection system, the dynamic fault trees of relay protection subsystem established. At present the main transformer protection and line protection device generally adopt double CPUs, CPU1 is to protect the CPU plug-in, and is the core plug-in, which mainly complete Protection action judgment, software and hardware self-test etc. CPU2 is to launch the CPU plug-in, which complete start and locking of protection function etc. When inadvertent operation, both CPU1 and CPU2 modules are malfunction, and CPU2 needs to precede CPU1. PAND is suitable to express this relationship. When refuse operation, As long as either CPU1 or CPU2 refuse operation, Protective devices are immovable. The conventional or gate is suitable to express this relationship. The failure of DO, DI and AI Plugs in relay protection may result in inadvertent operation and refuse operation, and their failure rates are equal. PSU failure may also lead to these two kinds of conditions. But because of its own with corresponding protection circuit, only refuse operation of the PSU is considered. The dynamic fault tree of relay protection system failure is shown in Figure 9.

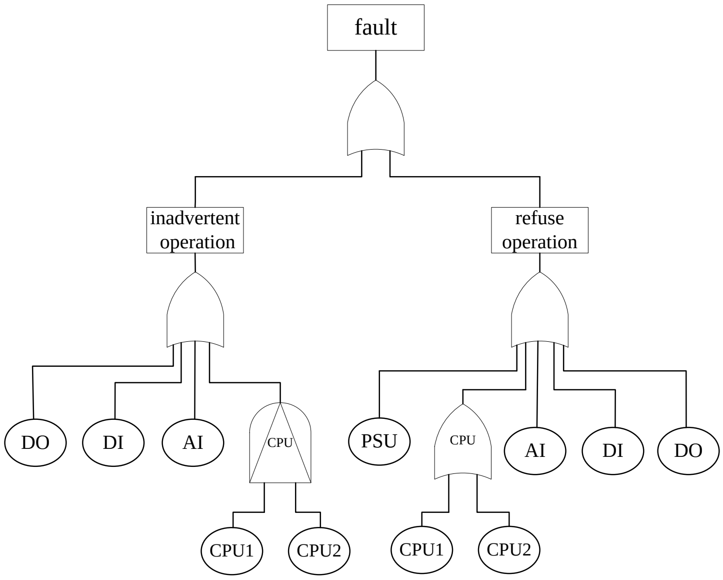

Figure 9. The Dynamic Fault Tree of Relay Protection System Failure

Dynamic fault tree analysis generally becomes static sub-tree and dynamic sub-tree. In Figure9 the inadvertent operation of the system is an example, its static sub-tree and dynamic sub-tree is shown in Figure 10.

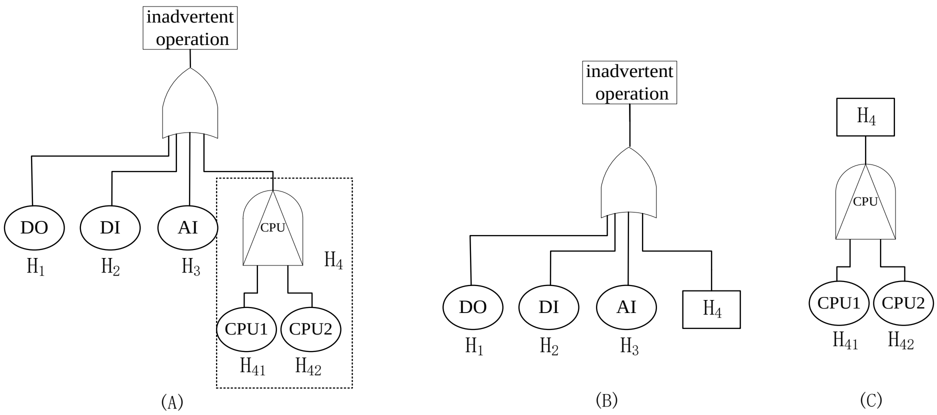

Figure 10. The Sub-tree of Inadvertent Operation (a) The Sub-tree (b) The Static Sub-tree (c) The Dynamic Sub-tree

The static sub-tree is solved by the BBD method. The decomposition process diagram of BBD is shown in Figure 11. The probability of the inadvertent operation is as follows:

$$P(H) = P(H_1) + P(H_2\overline{H_1}) + P(H_3\overline{H_2}\,\overline{H_1}) + P(H_4\overline{H_3}\,\overline{H_2}\,\overline{H_1}) \qquad (12)$$

As for the dynamic sub-tree, the Markov method is generally used to solve. The C diagram is a PAND in Figure 10, the analysis about it can get corresponding Markov chain as shown in Figure 12. “00” indicates that H41 and H42 normal; “10” said the H41 fault; “01” said the H42 fault; “F2” said H42 firstly fault, then H41 fault; “F1” said H41 firstly fault, then H42 fault.

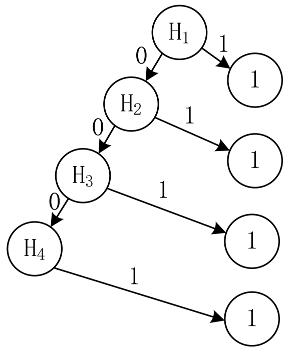

Figure 11. The Decomposition Process Diagram of BBD

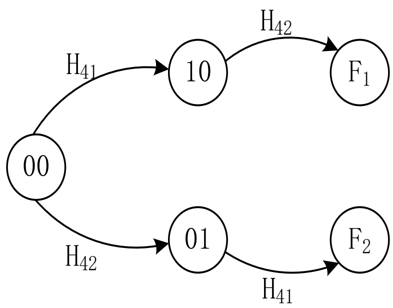

Figure 12. The Markov Chain of PAND

Considering H41 and H42 failure are independent of each other, the probability of failure of H4 is following:

$$P(H_4) = P(H_{41}) + P(H_{42}) \tag{13}$$

With a type relay protection of 220kV circuit as an example, this example has collected some data about the operation of relay protection, which is based on the actual operation experience and the statistical obtained in various fault. The specific parameters are shown in Table 1.

Table 1. Triangular Fuzzy Number to Represent the Failure Rate Data

module	inadvertent operation fuzzy failure rate($\times10^{-6}$h)	refuse operation fuzzy failure rate($\times10^{-6}$h)
CPU1	(14.1270,16.6200,19.1130)	(14.1270,16.6200,19.1130)
CPU2	(14.1270,16.6200,19.1130)	(14.1270,16.6200,19.1130)
DO	(7.9135,9.3100,10.7065)	(7.9135,9.3100,10.7065)
DI	(2.7965,3.2900,3.7835)	(2.7965,3.2900,3.7835)
AI	(8.5765,10.0900,11.6035)	(8.5765,10.0900,11.6035)
PSU	0	(10.0810,11.8600,13.6390)

When t=10000h, the membership functions of the fuzzy failure probability is shown in Figure 13, and according to this figure the median of fuzzy probability is 0.4212.

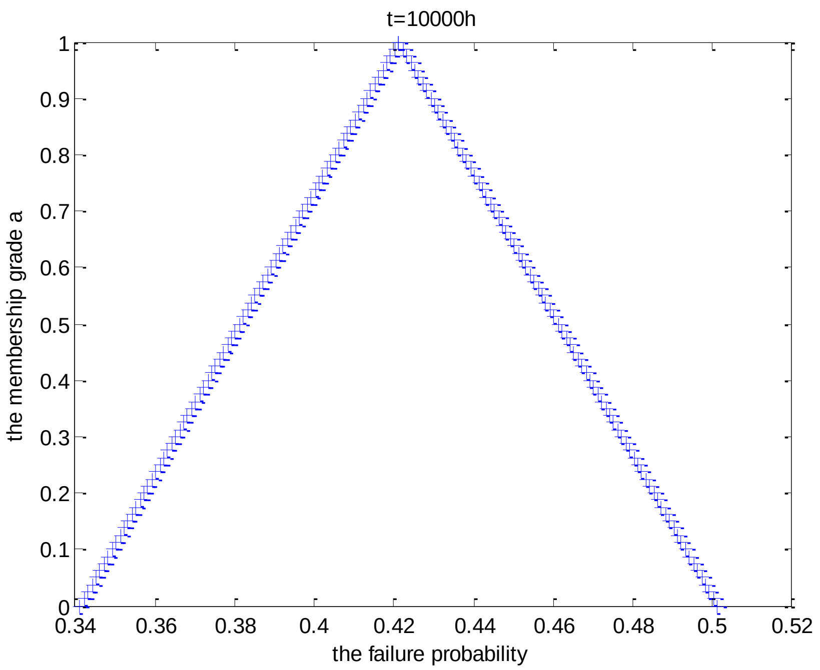

Figure 13. T=10000h the Membership Functions of the Fuzzy Probability

At a fixed level cut set, the reliability curve of the system as shown in Figure 14. The data line represents respectively the fuzzy reliability curve in cut set a=1, and the upper and lower limit curve of the fuzzy reliability in a=0.

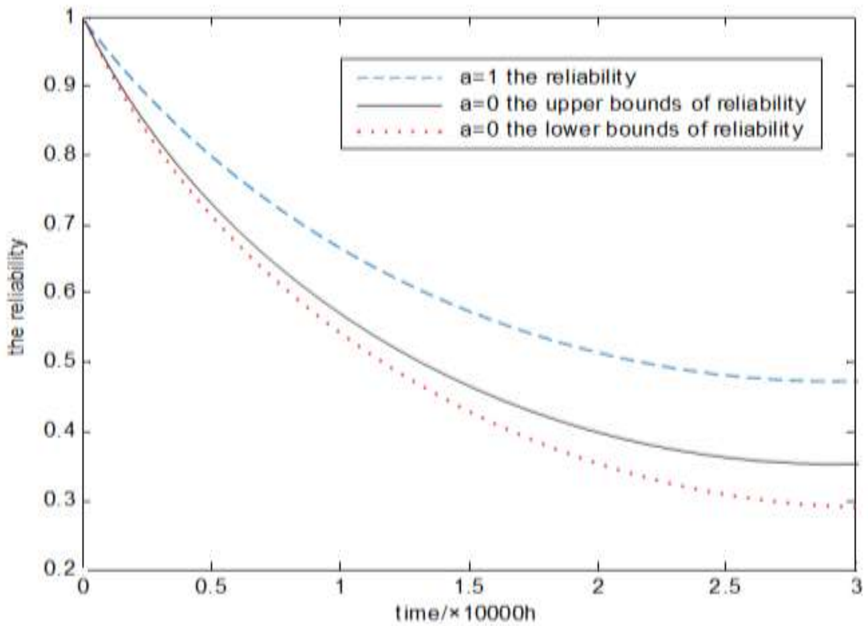

Figure 14. Fuzzy Reliability of the Cut Set in a=0 and a=1

6. Summary

Whether the relay protection system is reliable for fast and accurate action is directly related to the safe and stable operation of power system. According to the structural property of the relay protection system, the paper use these advantage that dynamic fault tree establishes the model, qualitatively and quantitatively evaluate in the system of relay protection. Fuzzy Markov model for reliability evaluation is established on the basis of the analysis of system structure and on the failure analysis, and gives full consideration to the effect which uncertain failure rate impact on system reliability evaluation. The model truly reflects the actual protection system, Simple modeling, easy to realize modularization and is suitable for different sizes, different protection systems. Through the application of Markov, it not only reduces the difficulty of Markov state division and the solution of the fault tree, but also plays the advantages of the two. The above example analysis shows that the model not only can effectively evaluate the reliability of relay protection system in the case of uncertainty, but also be applied to the reliability evaluation of different protection system.

Acknowledgments

This work is supported by National Nature Science Foundation of China under Grant 61304069, 61372195, 61371200, the Nature Science & Foundation of Liaoning Province under Grant 2013020124, the Fundamental Research Fund of Liaoning Provincial Education Department Key Laboratory under Grant LZ2014050 and the Scientific Research Fund of Liaoning Provincial Education Department under Grant L2014517. I would like to express my gratitude to all those who helped me during the writing of this thesis. I gratefully acknowledge the help of my supervisor, who has offered me valuable suggestions in the academic studies.

References

[1] Y. J. Guo, Editor, “Reliability Analysis of Power System”, Tsinghua University Press, Beijing, **(2003)**.
[2] F. S. Sun and X. H. Wang, “A new Method for Reliability Analysis of Protection in Power Systems”, Automation of Electric Power Systems, vol. 30, no. 32, **(2006)**.
[3] L. R. Castro and P. A. Crossley, “Reliability Evaluation of Substation Control System”, IEEE Pro-Gener, Trans and Distrib, vol. 146, no. 626, **(1999)**.
[4] X. T. Han, X. G. Yin and Z. Zhan, “Application of Fault Tree Analysis Method in Reliability Analysis of Substation Communication System”, Power System Technology, vol. 28, no. 56, **(2004)**.
[5] J. W. Guo, G. Liu and G. Q. Tang, “Markov Decision Process on Electric Equipments Maintenance Optimization”, Proceeding of the EPSA, vol. 16, no. 6, **(2004)**.
[6] K. D. Rao, V. Gopika and V. S. Rao, “Dynamic Fault Tree Analysis using Monte Carlo Simulation in Probabilistic Safety Assessment”, Reliability Engineering & System Safety, vol. 94, no. 872, **(2009)**.
[7] X. F. Xiong, Q. F. Ouyang and J. Q. Zhou, “Probabilistic Model for the Relay Protection System's Correct Failure Removal”, Automation of Electric Power Systems, vol. 31, no. 12, **(2007)**.
[8] A. Bobbio and C. R. Daniele, “Parametric Fault Trees with Dynamic Gates and Repair Boxes”, Proceedings of the Annual IEEE Reliability and Maintainability Symposium, **(2004)**, Los Angeles, USA.
[9] A. Bobbio, L. Portinale and M. Minichino, “Improving the Analysis of Dependable Systems by Mapping Fault Trees into Bayesian Networks”, Reliability Engineering & System Safety, vol. 71, no. 249, **(2001)**.
[10] J. B. Dugan, S. J. Bavuso and M. A. Boyd, “Dynamic Fault Tree for Fault Tolerant Computer Systems”, IEEE Transactions on Reliability, vol. 41, no. 363, **(1992)**.
[11] J. B. Dugan, K. J. Sullivan and D. Coppit, “Developing a Low Cost High-quality Software Tool for Dynamic Fault Tree Analysis”, IEEE Transactions on Reliability, vol. 49, no. 49, **(2000)**.
[12] L. Meshkat, J. B. Dugan and J. D. Andrews, “Dependability Analysis of Systems with on Demand and Active Failure Modes Using Dynamic Fault Trees”, IEEE Transactions on Reliability, vol. 51, no. 240, **(2002)**.
[13] H. Boudali, P. Crouzen and M. Stoelinga, “A Rigorous Compositional and Extensible Framework for Dynamic Fault Tree Analysis”, IEEE Transactions on Dependable and Secure Computing, vol. 7, no. 128, **(2010)**.
[14] D. Salvatore and P. Antonio, “Dependability Evaluation with Dynamic Reliability Block Diagrams and Dynamic Fault Tree”, IEEE Transaction on Dependable and Secure Computing, vol. 16, no. 4, **(2009)**.
[15] Y. Li, W. P. Wang, B. N. Liu, Z. Zhang and S. W. Xue, “Method for Complicated Electric System Reliable Degree Assessing Based on FTA and Fuzzy Evaluation”, Computer Measurement & Control, vol. 20, no. 2467, **(2012)**.

[16] K. E. Zeng, "Research on Operation Situation and Reliability Indices of Protective Relaying in Power System", Power System Technology, vol. 28, no. 83, **(2004)**.
[17] X. P. Xiong, J. C. Tan and X. N. Lin, "Reliability Analysis of Communication Systems in Substation Based on Dynamic Fault tree", Proceedings of the CSEE, vol. 34, no. 135, **(2012)**.
[18] L. H. Duan, A. M. Guo and Y. Pan, "Review on Dynamic Fault Tree Analysis", Electronic Product Reliability and Environmental Testing, vol. 31, no. 59, **(2013)**.
[19] P. C. Zhang and X. Gao, "Analysis of Reliability and Component Importance for All-digital Protective Systems", Proceedings of the CSEE, vol. 28, no. 77, **(2008)**.
[20] J. L. He, Z. Guo and X. J. Yang, "Reliability and Dynamic Performance Simulation of Relay Protection", Power System Technology, vol. 28, no. 18, **(2004)**.
[21] J. L. Wang, G. Wang and B. Li, "Reliability Modeling of a Protection System Based on the semi-Markov Process", Automation of Electric Power Systems, vol. 34, no. 6, **(2010)**.
[22] Z. H. Bie and X. L. Wang, "Research on Hybrid Method for Power System Reliability Evaluation", Chinese Power, vol. 34, no. 25, **(2001)**.
[23] X. L. Jiang, B. Zhang and X. S. Han, "Condition-based Maintenance Optimization for Power Equipment Based on Fuzzy Markov Processes", Journal of Shandong University (engineering science), vol. 44, no. 90, **(2014)**.
[24] W. H. Hou, P. C. Zhang and Y. Hu, "Reliability Analysis for Protection Systems Based on High Availability Automation Network", Power System Protection and Control, vol. 38, no. 44, **(2010)**.
[25] Z. H. Dai, Z. P. Wang and Y. J. Jiao, "The Relay Protection Reliability Data Collection System Design", Automation of Electric Power Systems, vol. 34, no. 47, **(2010)**.

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