The Efficient Offline Search System for High Risk Events of Power Systems Caused by Natural Disasters

TETSUSHI MIKI
Department of Electrical and Electronic Engineering
Anan National College of Technology
256 Aoki Minobayashi-Cho, Anan, 774-0017 Tokushima, JAPAN
tmiki@anan-nct.ac.jp http://www.anan-nct.ac.jp/

Abstract: - Power systems become large and complex, so the occurrence rates of a great deal of energy loss caused by faults become high. In this situation, the development of the efficient search system for high risk events of power systems is strongly required. Risk is defined as the product of energy loss and its occurrence rate, considering that the goal of power systems is the stable supply of power. This paper presents the offline search system which can search accurately and efficiently high risk events of power systems resulted from the loss of transient stability caused by natural disasters. It was applied to the model system composed of 3 generators and 9 buses. The results of application have clarified its effectiveness.

Key-Words: - Power Systems, Transient Stability, Risk, Natural Disasters, Critical Fault Clearing Time

1 Introduction

Power systems become large and complex, so the occurrence rates of a great deal of energy loss caused by faults become high. In this situation, the development of the efficient search system for high risk events of power systems is strongly required. Risk is defined as the product of energy loss and its occurrence rate, considering that the goal of power systems is the stable supply of power. Researches which are related to the search system for high risk events of power systems are classified into ones about online security assessment based on risk and the other about offline risk assessment by use of Monte Carlo simulation.

(1) Online security assessment based on risk

There are researches about security assessment based on risk caused by loss of transient stability [1], security assessment based on risk caused by overload [2], [3] and identifying high risk contingencies of substations for online security assessment [4]. The objective of these researches is online security assessment at full speed. Therefore, they do not show the efficient method for searching high risk events among all ones to be occurred in power systems.

(2) Offline risk assessment

There is the research about offline risk assessment of power systems by use of Monte Carlo simulation [5]. The objective of this research is the average risk assessment of power systems. Because a great number of simulation times are required in order to assess accurately high risk events with very low frequency, it is not appropriate to apply this method to search high risk events among all ones to be occurred in power systems.

Considering the above situation, this paper presents the developed offline search system which can search accurately and efficiently high risk events of power systems resulted from the loss of transient stability caused by natural disasters.

2 Efficient Search Method for High Risk Events of Power Systems

The efficient search method for high risk events of power systems caused by natural disasters has been developed in order to construct the search system [6], [7]. The flowchart of this method is shown in Fig.1. The steps of this flowchart are shown as follows.

(1) Generating probability density functions of loads

Load change data are classified into ones which have similar change patterns with seasons, date and time and the others which have non-similar change patterns with them. The probability density functions of loads are generated by the former data. The independent variables of these functions are common relative loads of power systems. The joint probability density functions of loads are generated by the latter data. The independent variables of these functions are each relative loads of power systems.

(2) Selecting representative natural disasters

Representative natural disasters which will cause high

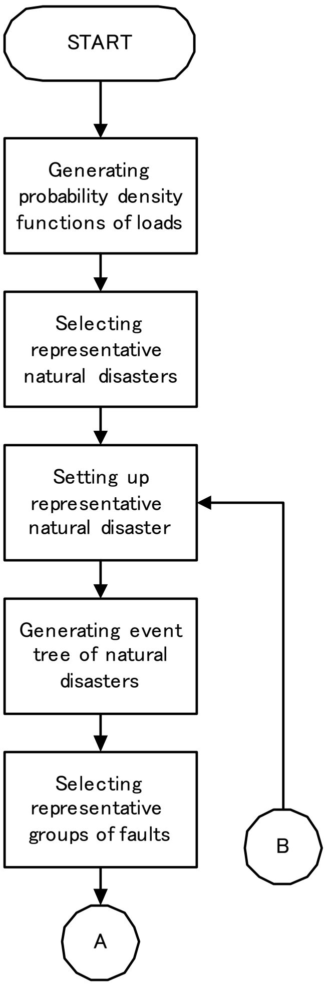

Fig. 1-(1/2). Flowchart for efficient research method for high risk events of power systems.

risk events are selected as follows.
1) Enumerating all natural disasters
All natural disasters to be occurred in power systems are enumerated. Representative natural disasters are concretely lightning, earthquake, typhoon, tornado, heavy snowfall and so on.
2) Selecting representative natural disasters
Representative natural disasters which will cause high risk events are selected based on the characteristics of the region where power systems present.
(3) Setting up representative natural disaster
Preceding natural disasters which will cause high risk events, the representative natural disaster to be assessed next is set up.
(4) Generating event tree of natural disasters
The event trees of natural disasters are generated based on statistics data of natural disasters. Their top events are natural disasters and their bottom events are groups of faults caused by natural disasters.

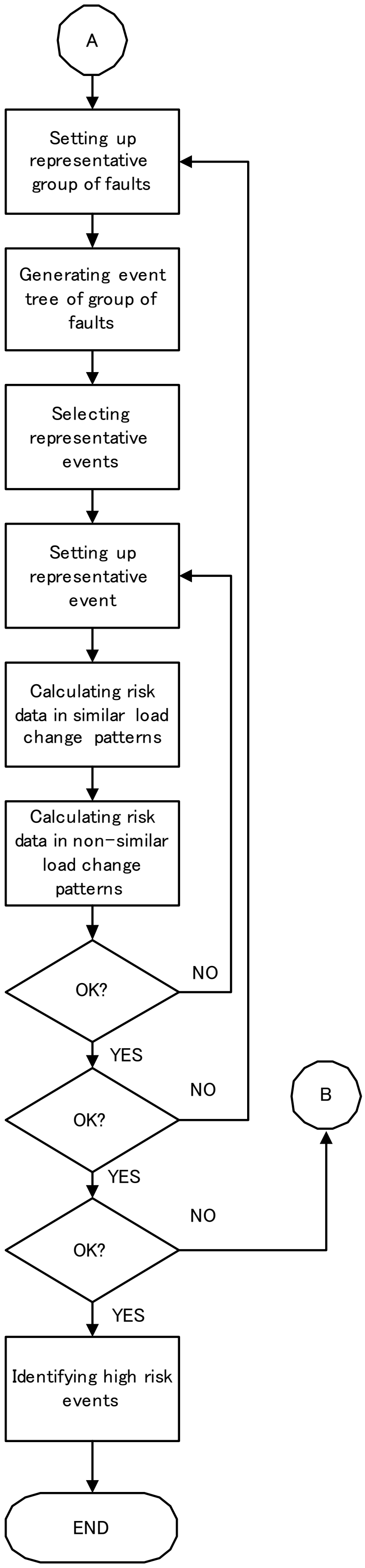

Fig. 1-(2/2). Flowchart for efficient research method for high risk events of power systems.

(5) Selecting representative groups of faults
Representative groups of faults are selected by product of estimated energy loss in bottom events and their occurrence rates.
(6) Setting up representative group of faults
Preceding representative group of faults which will cause high risk, the representative group to be assessed next is set up.
(7) Generating event tree of group of faults
Assuming that all protection systems act normally at first, event trees are generated. Next, the reliability of protection systems is analyzed and event trees in case of protection system failure are generated using analysis data. This new event trees are added to old ones. These event trees are knowledge bases which express synthetically the states transition of power systems after faults. The steps of generating event tree of group of faults are shown as follows [8].
1) Generating event tree in case of protection system normal action
Assuming that all protection systems act normally, the event trees for the set up fault are generated using relational data between loads and action sequences of protection systems. Event trees are generated by only high risk events, cutting events with lower risk than standard value.
2) Reliability analysis of protection systems
The reliability of protection systems is expressed by average probabilities that they are in normal or ith failure mode state. These average probabilities are obtained as follows.
a) The failure of protection systems is analyzed and failure mode (no action, error action of ith type, etc.) are identified.
b) The transition rates among normal and ith failure modes are obtained as follows.
· Failure rates are estimated based on past reliability data.
· Repair rates are estimated based on maintenance methods (inspection frequency, automation inspection devices, etc.).
c) The state transition process of protection system is expressed by Markov model. Pj (average probability that the protection system is in state j) is obtained by solving probability differential equations. This probability is the branch probability of event tree.
3) Addition of event tree in case of protection system failure
Assuming that protection systems act in set up modes, event trees are generated using relational data between loads and action sequences of protection systems. These event trees are added to already generated event tree. Event trees are generated by only high risk events, cutting events with lower risk than standard value.
(8) Selecting representative events
Representative events are selected by product of estimated energy loss in bottom events and their occurrence rates.
(9) Setting up representative event
Preceding event which will cause high risk, the representative event to be assessed next is set up.
(10) Calculating risk data in similar load change patterns
The flowchart for calculating risk data in similar load change patterns is shown in Fig.2.

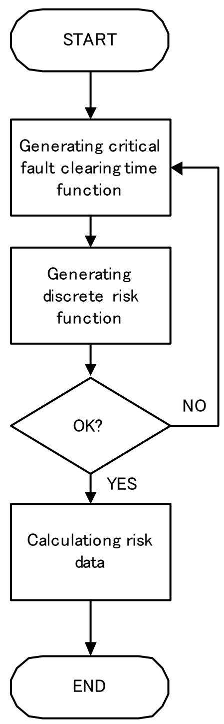

Fig. 2. Flowchart for calculating risk data in similar load change patterns.

1) Generating critical fault clearing time function
The critical fault clearing time is the boundary value between stable and unstable value of fault clearing time. The critical fault clearing time function CCT(W:load) is defined by taking notice of the fact that transient stability is mainly controlled by fault clearing time and load [9]. This function is knowledge base which expresses synthetically the transient stability of power systems after faults. Changing load roughly at first and finely later, representative events are simulated. Based on simulation data, critical fault clearing time functions is generated. The flowchart for

generating critical fault clearing time functions is shown in Fig.3. The critical fault clearing time CCT is calculated using the bisection algorithm [10]. The steps of this flowchart are shown as follows.

a) Setting up load

The load W is set up.

b) Setting up initial fault clearing time CT1,CT2

The lower stability limit CT1 and upper stability limit CT2 is set up, considering that the finally calculated critical fault clearing time CCT will be between CT1 and CT2.

c) Calculating fault clearing time CT

The mid-point value CT which is fault clearing time in the next simulation is calculated by averaging stability limit CT1 and CT2.

d) Simulating transient phenomena caused by faults of power systems

At first, the load flows before the occurrence of fault are calculated based on the data about load and power system. Next, the transient phenomena after the occurrence of fault are calculated based on the data about fault, initial load flow and power system.

e) Check of system stability

The system stability is checked based on results of simulation. If it is found that the system is stable, then the lower stability limit CT1 of interval is replaced by the mid-point value CT. Otherwise, the upper value CT2 is replaced by the mid-point value CT. Because the critical fault clearing times of generators are generally different, they have different CCT functions classified into some modes. Therefore, the system stability must be checked in all modes.

f) Check of calculation precision

The calculation precision is checked by comparing the difference between CT1 and CT2 with the required precision e. If the difference is smaller than e, then CCT equals CT1. Otherwise, step c) is processed next.

g) Check of request of changing load

It is checked if changing load is required in order to make graphs of CCT functions. If it is found that changing load is required, then load is changed according to the algorithms previously developed in order to generate efficiently CCT functions and step a) is processed next [11]. Otherwise, graphs of CCT functions expressed discretely are made based on CCT data in various loads.

2) Generating discrete risk function

The discrete risk function Rij(W) of fault i, bottom event j is generated as follows, cutting the low risk region of function.

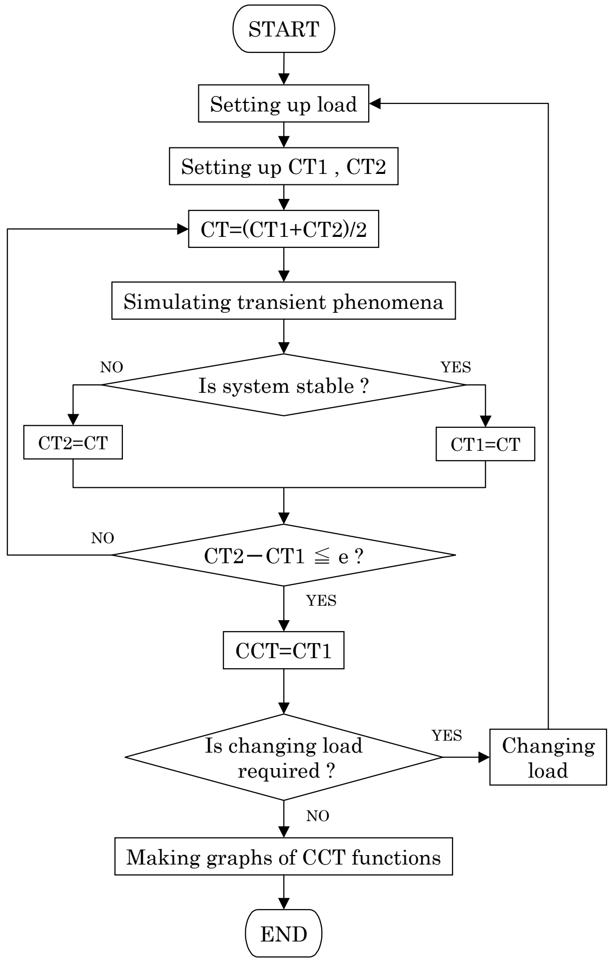

Fig. 3. Flowchart of generation of critical fault clearing time functions.

$$Rij(W) = FiPj \times \sum_{m=1}^{m=mt} PL(W)Cijm(W)Rijm(W)Tijm(W)W \quad (1)$$

Where

W : load

Fi : occurrence rate of fault i

Pj : branch probability from top event to bottom event j

mt : total mode number of instability

PL(W) : probability density function of load

Cijm(W) : function for discriminating occurrence of instability defined as follows

$CCTijm(W) - CT > 0$

0 (stable)

$CCTijm(W) - CT \leq 0$

1(unstable)

Where
CCTijm(W) : critical fault clearing time function of fault i, bottom event j, mode m,
CT : fault clearing time
Rijm(W) : ratio of average energy loss of fault i, bottom event j, mode m to total average energy in normal state
Tijm(W) : average fault duration time of fault i, bottom event j, mode m
3) Check of request of changing load
The load region with high risk is identified by discrete risk function. If changing load is not required in order to calculate final risk data, the next step is processed. Otherwise, step 1) is processed next.
4) Calculating risk data
The risk data Rijk of fault i, bottom event j, load k is calculated as follows.

$$Rijk = \int_{Wkb}^{Wkt} Rij(W)dW \qquad (2)$$

Where
Wkb : bottom(minimum)value of load k
Wkt : top(maximum)value of load k
(11) Calculating risk data in non-similar load change patterns
The flowchart for calculating risk data in non-similar load change patterns is shown in Fig.4 [12]. The steps of this flowchart are shown as follows.
1) Selecting representative non-similar load change patterns
The joint probability density functions of loads with non-similar change patterns are integrated from bottom to top values of each discrete width. Non-similar load change patterns are sorted according to integrated values. Only non-similar load change patterns with high integrated values are selected as representative ones.
2) Setting up representative no-similar load change patterns
Preceding representative non-similar loads change patterns which have high integrated vales, the pattern to be assessed next is set up.
3) Calculating average energy loss
The average energy loss WTAijl of fault i, bottom event j, non-similar load change pattern l is calculated based on simulation results of transient phenomena.
4) Check of calculating representative non-similar load change patterns
If average energy losses of all representative non-similar load change patterns are calculated, the next step is processed. Otherwise, step 2) is processed next.

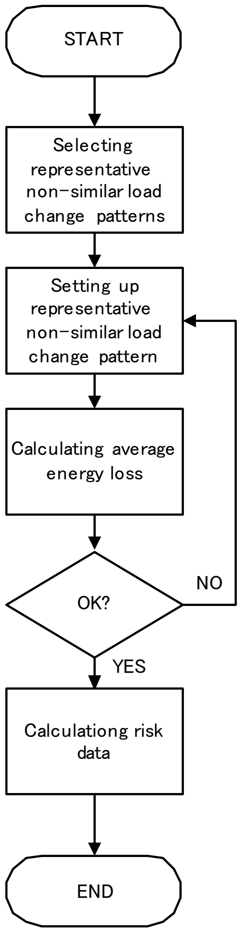

Fig. 4. Flowchart for calculating risk data in non-similar load change patterns.

5) Calculating risk data
The risk data Rijl of fault i, bottom event j, non-similar load change pattern l is calculated as follows.

$$Rijl = FiPjWTAijl \qquad (3)$$

Where
Fi : occurrence rate of fault i
Pj : branch probability from top event to bottom event j
(12) Check of calculating representative events
If risk data of all representative events are calculated, the next step is processed. Otherwise, step (9) is processed next.
(13) Check of calculating representative group of faults

If risk data of all representative groups of faults are calculated, the next step is processed. Otherwise, step (6) is processed next.

(14) Check of calculating representative natural disasters

If risk data of all representative natural disasters are calculated, the next step is processed. Otherwise, step (3) is processed next.

(15) Identifying high risk events

High risk events are identified by sorting risk data according to values.

3 Efficient Offline Search System for High Risk Events of Power systems

Based on the developed efficient search method, the efficient offline search system for high risk events of power systems has been constructed on a standard personal computer. Its general software constitution is shown in Fig.5. It is composed of code, data and knowledge bases. The components are shown as follows.

(1) Code

There is the following one item.

1) Code for transient phenomena simulation

This code inputs condition data of simulation and simulates transient phenomena of power systems after faults by solving simultaneous differential equations. Finally, it outputs results of simulation.

(2) Data

There are the following eight items.

1) Natural disaster data

They are natural disaster data to be occurred in power systems.

2) Representative natural disaster data

They are natural disaster data which are selected based on the characteristics of the region where power systems present.

3) Representative group data of faults

They are group data of faults which are selected by product of estimated energy loss in bottom events and their occurrence rates.

4) Condition data of simulation

They are data which set the conditions of next simulation when event trees and critical fault clearing time functions are generated. They are concretely various parameters of power systems, load, kinds / locations of faults and fault clearing times and so on.

5) Result data of simulation

They are data gained by simulating transient phenomena of power systems after faults and are

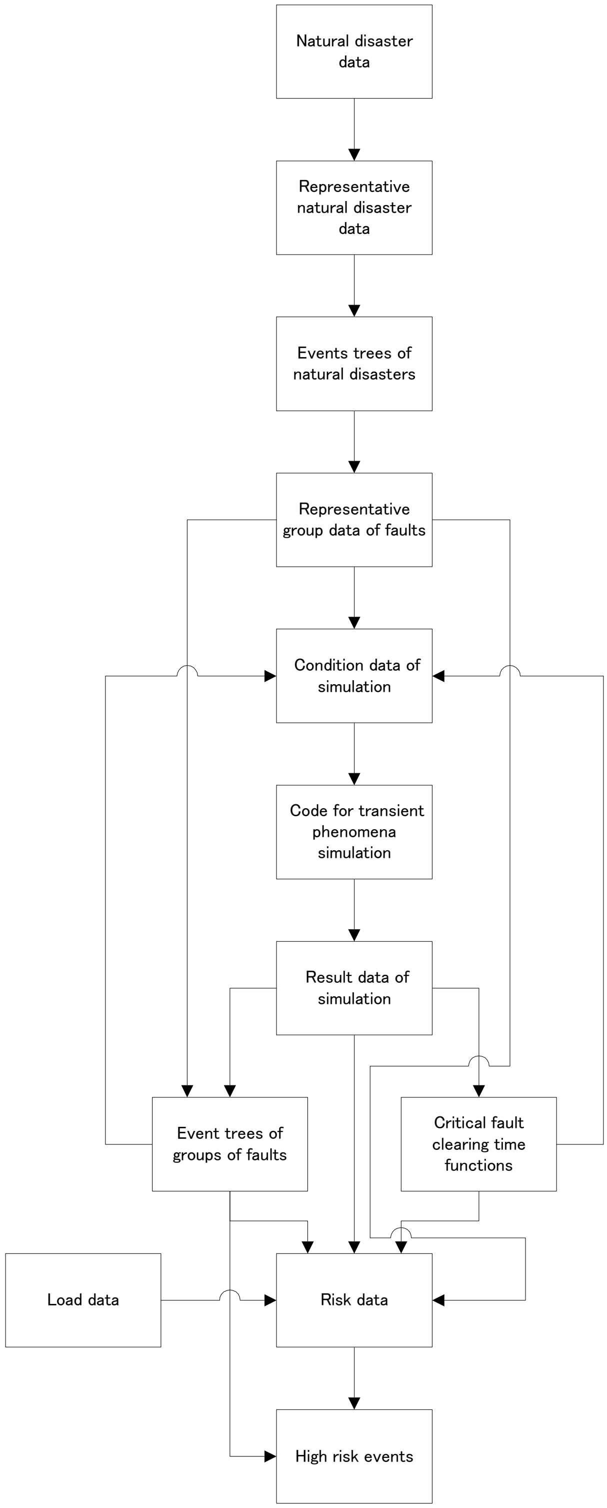

Fig. 5. General software constitution of efficient research system for high risk events of power systems.

displayed on CRT after being transformed into analog trend graphs, for digital data are incomprehensible.

6) Load data

They are data gained by gathering change patterns of load with time.

7) Risk data

In case of similar load change patterns, they are data gained by integrating discrete risk functions which are generated based on representative fault data, event trees, load data, critical fault clearing time functions and result data of simulation. In case of non-similar load change patterns, they are data which are generated based on representative fault data, event trees, load data and result data of simulation.

8) High risk events

They are data which are gained by sorting risk data according to values. Their concrete contents are stored in the correspondent part of event trees.

(3) Knowledge bases

There are the following three items.

1) Event trees of natural disasters

They are knowledge bases which express synthetically the transition of events occurred in power systems after natural disasters. They are composed of the following three elements.

a) Events occurred in power systems

b) Trees which show causalities among events

c) Branch probabilities from higher events to lower ones

2) Event trees of groups of faults

They are knowledge bases which express synthetically the transition of events occurred in power systems after faults. They are composed of the following three elements.

a) Events occurred in power systems

b) Trees which show causalities among events

c) Branch probabilities from higher events to lower ones

3) Critical fault clearing time functions

They are knowledge bases which express synthetically the transient stability of power systems after groups of faults.

4 Application to Model Power Systems

4.1 Conditions of Application

In order to confirm the effectiveness of the developed system, it was applied to a model power system under the following conditions.

(1) The constitution of a model power system is shown in Fig.6. The capacities of generators are 247.5, 192 and 128MVA in order of numbers.

(2) Only the loss of transient stability is simulated among fault cascading phenomena.

(3) All generators lose transient stability in occurrence of plural faults.

(4) The average fault duration time of one fault is 1 hour and that of plural faults is 10 hours.

(5) The probability density function of load with similar change pattern is shown in Fig.7.

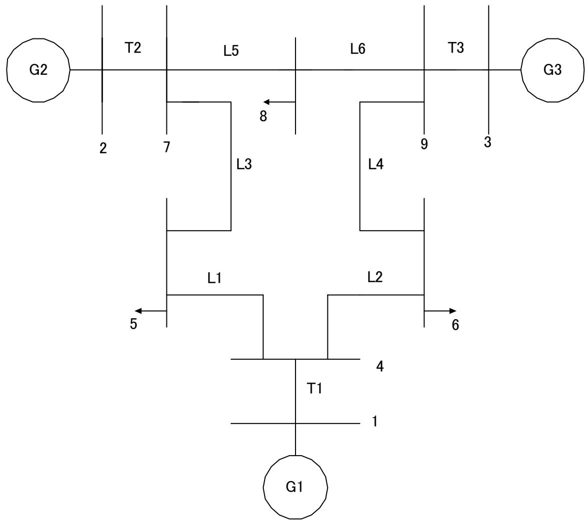

Fig. 6. Constitution of model power system.

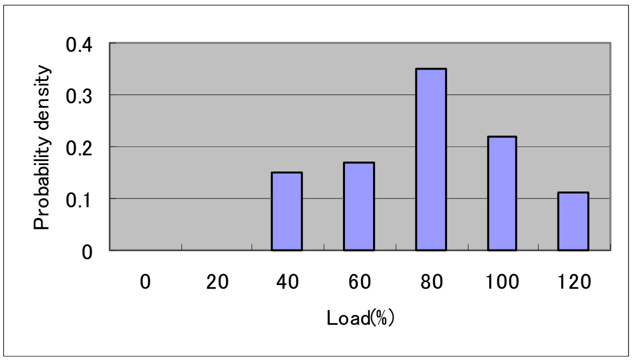

Fig. 7. Probability density function of load.

4.2 Process of Search in Case of Earthquake

The outline of search process of high risk events is shown as follows.

(1) Generating probability density functions of loads

The total probability that the model power system is in non-similar load change patterns is 0.4.

(2) Selecting representative natural disasters

Earthquakes are selected as representative natural disasters. The definition of level of earthquake and its occurrence rate is shown in Table 1.

(3) Generating event tree of natural disasters

Transition probability from top to bottom events in event tree of earthquake is shown in Table 2.

Table 1. Definition of level of earthquake and its occurrence rate.

Number of level	Seismic intensity x (Japanese scale)	Occurrence rate (time/year)
1	5.5≦x<6.0	0.1
2	6.0≦x<6.5	0.05
3	6.5≦x<∞	0.01

Table 2. Transition probability from top to bottom events in event tree of earthquake.

Number of level	No fault	One fault	Plural faults
1	0.95	0.05	0
2	0.1	0.8	0.1
3	0	0.2	0.8

(4) Selecting representative groups of faults

LLG (two-phase-line-to-line-to-ground-fault) in buses are selected as representative fault in case of one fault based on results of simulation.

(5) Generating event tree of group of faults

When LLG occurs, large currents flow. The over-current-relays detect these currents and clear the fault. This protection actions are carried out in any load. If CT is smaller than CCT, the power system is stable, otherwise, it is unstable. If protection systems do not act by failures, the probability of energy loss will become high. But, the risk will small, for the failure rate of no action is very small. The event tree in case of no action is cut because of the above reason. The generated event tree is shown in Fig. 8.

(6) Selecting representative events

The events which satisfy the following conditions are selected as representative ones.

1) LLG occurs in buses.
2) Protection systems act normally.
3) Energy loss occurs by loss of transient stability.

(7) Calculating risk data in similar load change patterns

1) Generating critical fault clearing time function

The critical fault clearing time functions of events caused by LLG occurred in various buses are shown in Fig.9. The unit of CCT is cycle and one cycle is 0.017 seconds. This graph makes it clear that the event caused by the above fault occurred in the bus B7 has the highest risk.

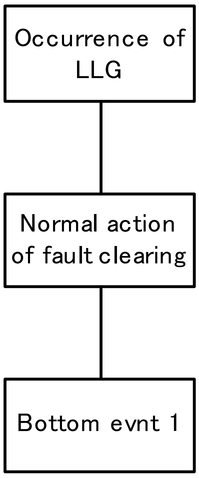

Fig. 8. Event tree caused by LLG.

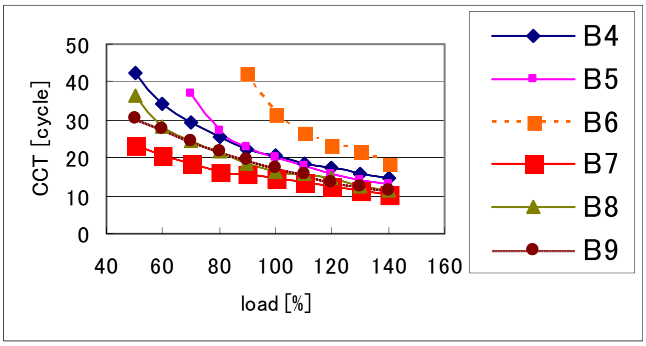

Fig. 9. Change of critical fault clearing time functions by fault locations.

2) Generating discrete risk function and calculating risk data

The discrete risk functions per one LLG occurred in the bus B7 in various CT are shown in Fig. 10. The total risk of all loads is defined as 100% in case that the average fault duration time is 1 hour and average power loss is the rated power.

(8) Calculating risk data in non-similar load patterns

When CT is 25 cycles, high risk data in non-similar load change patterns are calculated.

(9) Identifying high risk events

High risk data of one fault are shown in Table 3. The numbers of load change patterns are numbered according to values of risk. High risk data per year in each level of earthquake are shown in Table 4.

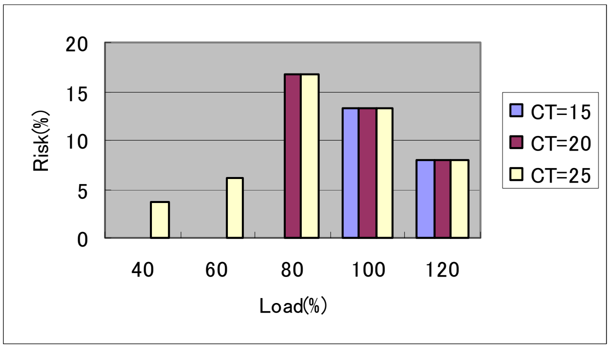

Fig. 10 Change of discrete risk functions by CT(fault clearing time).

Table 3. High risk data of one fault.

Number of load change pattern	Load of B5 (%)	Load of B6 (%)	Load of B8 (%)	Risk (%)
1	80	80	80	17
2	100	100	100	13
3	80	80	100	10

Table 4. High risk data per year in each level of earthquake.

Level of earthquake	Risk (%/year)
1	0.34
2	2.08
3	2.27

4.3 Process of Search in Case of Lighting

The outline of search process of high risk events is shown as follows.
(1) Generating probability density functions of loads
The total probability that the model power system is in non-similar load change patterns is 0.4.
(2) Selecting representative natural disasters
Lightning is selected as representative natural disasters. Lightning occurrence data have been collected with the lightning location systems operated by electric power companies in Japan [13]. The paper which reports the above fact gives the following data.
1) Nine-year (1992-2000) average lightning stroke frequency maps in summer, winter and the whole year
2) Graph (X axis: annual number of lightning strokes, Y axis: outage / 100km / year) which shows the relation between the annual number of lightning strokes and the frequency of the faults on transmission lines. This graph shows that the number of faults is almost proportional to the annual number of lighting stokes.
(3) Generating event tree of natural disasters
Based on the above data, event tree is generated as follows.
The occurrence rate of lightning stroke = 550,000/year
Transition probabilities from top to bottom events
No fault = 0.9999908, One fault = 0.0000092
Plural faults in separated places = 0
Based on the above data, ANOF (the annual number of one fault / 100km) is calculated as follows.
ANOF = 550,000$\times$0.0000092 = 5.06
(4) Selecting representative groups of faults
LLG (two-phase-line-to-line-to-ground-fault) in buses are selected as representative fault in case of one fault based on results of simulation.
(5) Generating event tree of group of faults
(6) Selecting representative events
The events which satisfy the following conditions are selected as representative ones based on the generated event tree.
1) LLG occurs in buses.
2) Protection systems act normally.
3) Energy loss occurs by loss of transient stability.
(7) Calculating risk data in similar load change patterns
1) Generating critical fault clearing time function
2) Generating discrete risk function and calculating risk data
(8) Calculating risk data in non-similar load patterns
(9) Identifying high risk events
The highest event is occurred in case that all loads are 80% (70%~90%) of the rated load. In case of that the equivalent length of the bus is 50m, the high risk data per year in case of lightning are shown as follows.
Optimistic case = 0.014 (% / year)
Average case = 0.043 (% / year)
Pessimistic case = 0.129 (% / year)
Risk data of a equivalent real power system in a electric power company in Japan = 0.039 (% / year)
The value of risk data is relatively defined as 100% in case that the average fault duration time is 1 hour and average power loss is the rated power.

4.4 Results of Application

The results of application have clarified the following facts.

(1) The high risk events of power systems can be accurately and efficiently searched by using the developed system.

(2) The effect of fault clearing time on risk can easily assessed by using critical fault clearing time functions.

(3) The accuracy and efficiency of search depends on the power system model of simulator and input data.

5 Conclusion

The results of application of the developed system to the model system have clarified its effectiveness.

In order to apply it to real power systems, the following works are required in the future.

(1) It will be applied to various power systems and will be improved by results of assessment.

(2) High risk events of natural disasters except earthquake and lightning will be searched.

(3) The method in order to improve the accuracy of data base of natural disasters will be researched.

This research was carried out, receiving Grant-in-Aid for Scientific Research given by Japan Society for the Promotion of Science : Foundation Research (C) 18560293.

References:

[1] C.Fu and A.Bose, Contingency Ranking Based on Severity Indices in Dynamic Security Analysis, *IEEE Trans. Power Systems,* Vol.14, No.3, 1999, pp. 980-986.

[2] M.Ni, J.D.McCally, V.Vittal and T.Tayyib, Online Risk-Based Security Assessment, *IEEE Trans. Power Systems,* Vol.18, No.1, 2003, pp. 258-265.

[3] M.Ni, .J.D.McCally, V.Vittal, S.Greene, C.Ten, V.S.Ganugula and T.Tayyib, Software Implementation of Online Risk-Based Security Assessment, *IEEE Trans. Power Systems,* Vol.18, No.3, 2003, pp. 1165-1172.

[4] Q.Chen and J.D.McCalley, Idenifying High Risk N-K Contingencies for Online Security Assessment, *IEEE Trans. Power Systems,* Vol.20, No.2, 2005, pp. 823-834.

[5] D.S.Kirschen, K.R.W.Bell, D.P.Nedic, D.Jayaweera and R.N.Allan, Computing the Value of Security, *IEE Proc.-Gener. Transm. Distrib.* Vol.150, No.6, 2003, pp.673-678.

[6] T.Miki, The Efficient Search Method for High Risk Events of Power Systems Caused by Natural Disasters, *Proceedings of the 7th WSEAS International Conference on Power Systems*, Vol.1, 2007, pp.168-172.

[7] T. Miki, Consideration of Uncertainty Factors in Search for High Risk Events of Power Systems Caused by Natural Disasters, *WSEAS Transactions on Power Systems,* Issue 3, Vol. 3, 2008, pp. 76-81.

[8] T.Miki, D.Okitsu, M.Kushida and T.Ogino, Development of a hybrid Type Assessment Method for Power System Dynamic Reliability, *Proceedings of the IEEE International Conference on System, Man, and Cybernetics*, Vol.1, 1999, pp. 968-973.

[9] T. Miki, D.Okitsu, E.Takashima, Y.Abe and M.Tano, Power System Transient Stability Assessment Using Critical Fault Clearing Time Functions, *Proceedings of the IEEE/PES Transmission and Distribution Conference and Exhibition 2002 : Asia Pasific,* Vol.3, 2002, pp. 1514-1517.

[10] S.Abreshaid, R.Billinton and M.Fotuhi-Firuzabad, Probabilistic Transient Stability Studies Using the Method of Bisection, *IEEE Trans. Power Systems,* Vol.11, 1996, pp. 1990-1995.

[11] T. Miki, R.Sugino and Y.Kono, The Efficient Generation Method of Critical Fault Clearing Time Functions for Power System Transient Stability Assessment, *WSEAS Transactions on Computer,* Issue 1, Vol. 2, 2003. pp. 116-121.

[12] T. Miki, The Efficient Search Method for High Risk Events of Power Systems with Similar and Non-similar Load Change Patterns, *WSEAS Transactions on Power Systems,* Issue 4, Vol. 1, 2006, pp. 721-726.

[13] S.Yokoyama, Lightning Detection and Lightning Protection of Power Systems in Japan, *Proceedings of the IEEE/PES Transmission and Distribution Conference and Exhibition 2002: Asia Pacific,* Vol.1, 2002, pp.546-551.