The offline effect assessment system of design factors on search for high risk events of power systems

Tetsushi Miki

***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 method 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 developed offline system which can assess accurately and efficiently effects of design factors on search for high risk events caused by loss of transient stability of power systems. Being focused on control systems, it was applied to the model system composed of 3 generators and 9 buses. The results of application have clarified its effectiveness.

***Keywords*—**Critical Fault Clearing Time, Power Systems, Risk, Transient Stability

I. 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 method 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 method for high risk events 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, the author developed the search method for high risk events of power systems caused by loss of transient stability which is the most important characteristic to assess in power systems [6]. Moreover, it was extended to the search for high risk events of power systems caused by natural disasters [7], [8].This method gains the high search efficiency by use of knowledge bases. But, the final goal is to decide the optimum plan which can reduce efficiently risk of high risk events and make the power system with low risk according to it. First of all, it is necessary to develop the system which can assess accurately and efficiently effects of design factors on high risk events caused by loss of transient stability of power systems. This paper presents the developed offline effect assessment system with the above abilities.

II. PROCEDURE EFFICIENT SEARCH METHOD FOR HIGH RISK EVENTS OF POWER SYSTEMS

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. All functions are expressed by discrete ones with discrete width which are selected by considering the tradeoff between the accuracy and time of calculation.

(2) Selecting representative faults

Representative faults which will cause high risk events are selected as follows.

1) All faults to be occurred in power systems are enumerated.

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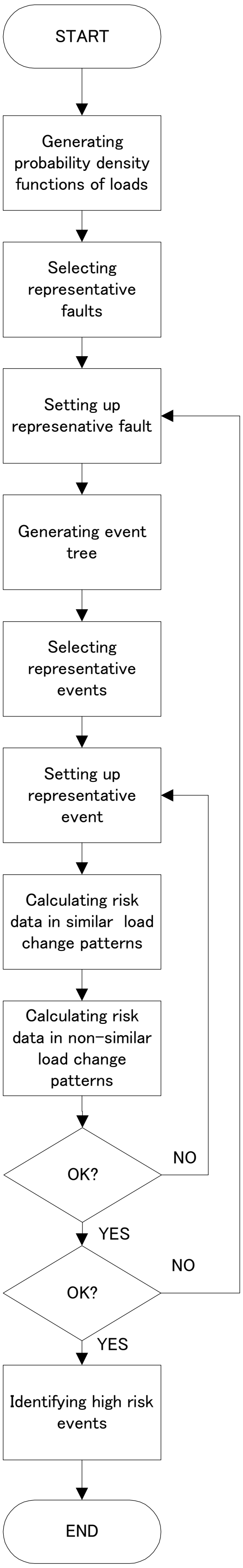

Fig. 1 flowchart for efficient research method for high risk events of power systems

Fault data base is made by classifying them based on kinds and locations of faults.

2) Faults which will cause high risk events are searched based on the following heuristic knowledge bases.

a) Multi-phase-faults will cause high risk events with high probabilities.

b) Faults occurred in buses which connect many lines will cause high risk events with high probabilities.

c) Faults occurred in neighborhood of generators with small capacities will cause high risk events with high probabilities.

3) Transient phenomena of faults in border are simulated and representative faults are finally selected based on results of simulation.

(3) Setting up representative fault

Preceding faults which will cause high risk events, the representative fault to be assessed next is set up.

(4) Generating event tree

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 are shown as follows [9].

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.

(5) Selecting representative events

Representative events are selected by product of estimated energy loss in bottom events and their occurrence rates.

(6) Setting up representative event

Preceding event which will cause high risk, the representative event to be assessed next is set up.

(7) Calculating risk data in similar load change patterns

The flowchart for calculating risk data in similar load change patterns is shown in Fig.2. The steps of this flowchart are shown as follows.

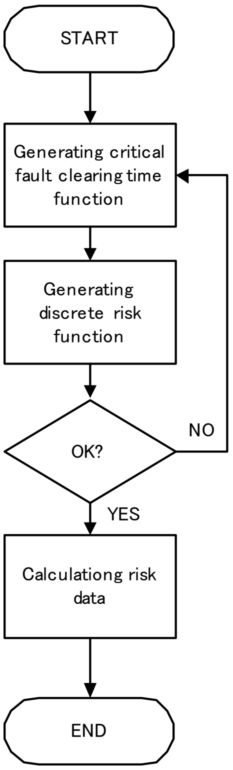

Fig. 2 flowchart for calculating risk data in similar load change patterns

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 [10]. 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 [11]. 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 [12]. The steps of this flowchart are shown as follows [6], [13].

a) Setting up load

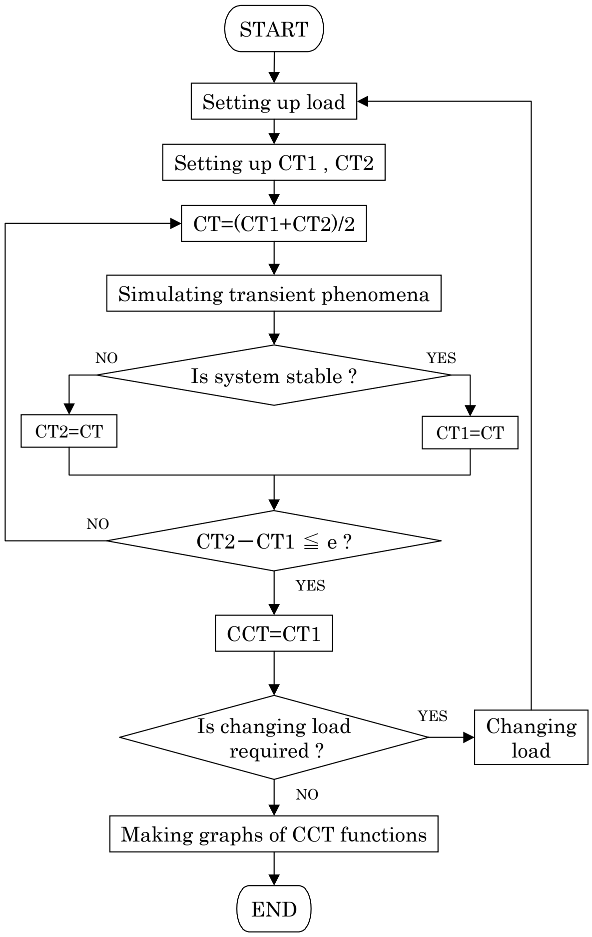

Fig. 3 flowchart of generation of critical fault clearing time functions

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. This function is knowledge base which expresses synthetically the risk of power systems after faults.

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

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.

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

Where

Wkb : bottom(minimum)value of load k

Wkt : top(maximum)value of load k

(8) 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. The steps of this flowchart are shown as follows.

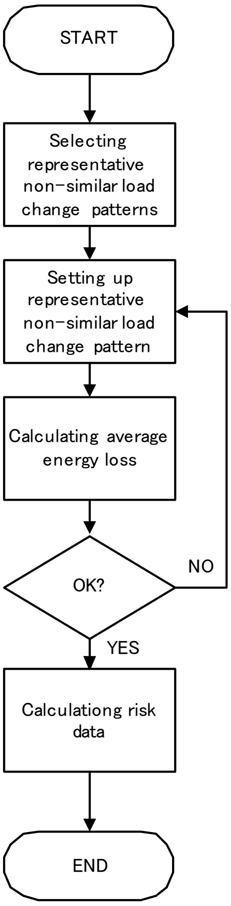

Fig. 4 flowchart for calculating risk data in non-similar load change patterns

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 are calculated, the next step is processed. Otherwise, step 2) is processed next.

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

(9) Check of calculating representative events

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

(10) Check of calculating representative faults

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

(11) Identifying high risk events

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

III. EFFECT ASSESSMENT METHOD OF DESIGN FACTORS ON SEARCH FOR HIGH RISK EVENTS

The method which can assess accurately and efficiently effects of design factors on search for high risk events has been developed. The efficiency of its search is improved by using the already calculated search data. The flowchart of this method is shown in Fig.5. The steps of this flowchart are shown as follows.

(1) Selecting all design factors for detail assessment

When there are many design factors for assessment, preliminary assessment is carried out in order to assess efficiently the effects of design factors on search for high risk events.

1) All design factors for preliminary assessment are enumerated.

2) From the above data, design factors for detail assessment are selected based on the following heuristic knowledge base.

a) Design factors which can reduce effectively risk of power systems should be preferentially assessed.

b) Design factors which can be changed by low costs should be preferentially assessed.

c) Design factors which are available should be preferentially assessed.

(2) Setting up design factor for detail assessment

Preceding design factors which can reduce effectively risk of power systems, the design factor to be assessed next is set up.

(3) Classifying set up design factor

The set up design factor is classified as follows.

1) Category 1

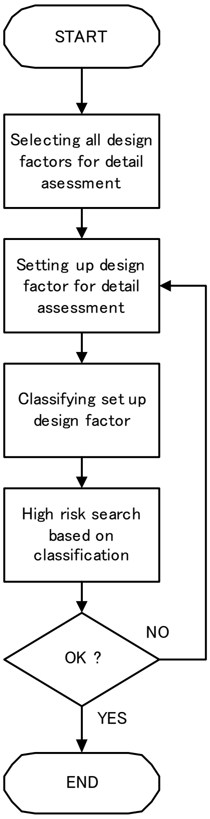

Fig. 5 flowchart for effect assessment method

a) Constitutions of power system and so on

2) Category 2

a) Components composed of power system, such as generators, control systems and protection systems

b) Emergency / restoration control against faults and so on

3) Category 3

a) Probability density functions of load

b) Occurrence rates of faults

c) Reliability of protection systems and so on

(4) High risk search based on classification

1) Category 1

When constitutions of power systems are changed, data of the present power system can not be reused. Therefore, all steps of search are must be carried out from the beginning.

2) Category 2

It is indispensable to simulate transient phenomena caused by faults of power systems and calculate risk data. But, data used in search of the present power system can be reused in case of data independent of simulation data. The efficiency of search can be improved by using this method.

3) Category 3

It is indispensable to collect and calculate concerned data. But, it is not necessary to simulate transient phenomena caused by faults of power systems. Risk data can be easily calculated by using equations (1), (2). The efficiency of search can be improved by using this method.

(5) Check of assessing all design factors for detail

assessment

If all design factors are assessed, the flowchart is ended. Otherwise, step (2) is processed next.

IV. EFFECT ASSESSMENT SYSTEM OF DESIGN FACTORS ON SEARCH FOR HIGH RISK EVENTS

Based on the developed effect assessment method, the effect assessment system of design factors on search for high risk events of power systems has been constructed on a standard personal computer. Its general software constitution is shown in Fig.6 (a) and Fig.6 (b).

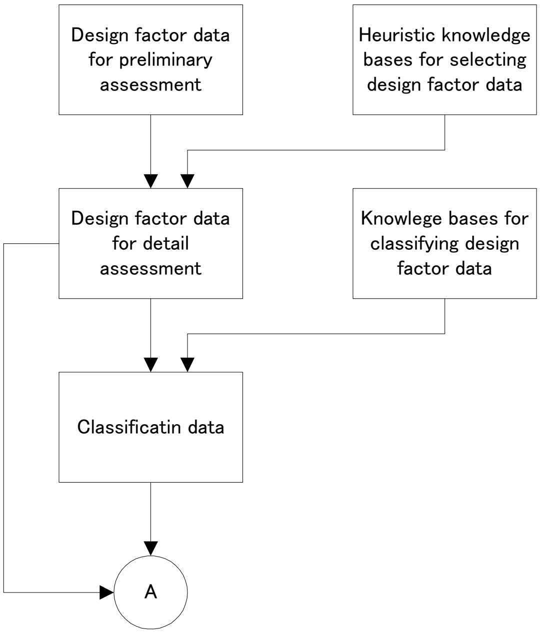

Fig.6 (a) general software constitution of effect assessment system (the upper part)

It is composed of code, data and knowledge bases. The components are shown as follows.

1) Code:

There is the following one item.

a) 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 eleven items.

a) Design factor data for preliminary assessment

They are data which are enumerated for preliminary assessment.

b) Design factor data for detail assessment

They are data which are selected for detail assessment.

c) Classification data

They are data which are classified in the tree categories based on knowledge bases for classifying design factor data.

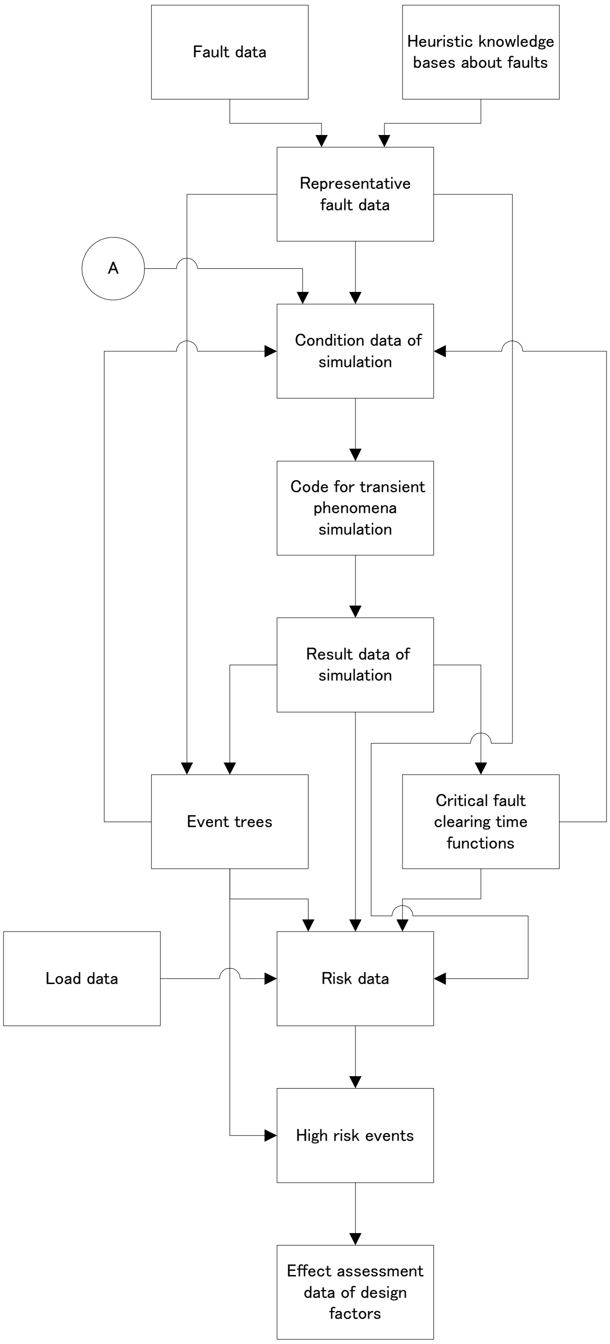

Fig.6 (b) general software constitution of effect assessment system (the lower part)

d) Fault data

They are all fault data to be occurred in power systems.

e) Representative fault data

They are fault data which are searched based on heuristic knowledge bases about faults and will cause high risk events.

f) 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.

g) Result data of simulation

They are data gained by simulating transient phenomena of power systems after faults and are displayed on CRT after being transformed into analog trend graphs, for digital data are incomprehensible.

h) Load data

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

i) 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.

j) 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.

k) Effect assessment data of design factors

They are data gained by assessing effects of design factors on search for high risk events.

3) Knowledge bases

There are the following five items.

a) Heuristic knowledge bases for selecting design factor data for detail assessment

They are knowledge bases which are used for selecting design factor data for detail assessment from ones for preliminary assessment.

b) Knowledge bases for classifying design factor data for detail assessment

They are knowledge bases which are used for classifying design factor data for detail assessment.

c) Heuristic knowledge bases about faults

They are knowledge bases which are used for selecting representative fault data from all fault data.

d) Event trees

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.

- Events occurred in power systems
- Trees which show causalities among events
- Branch probabilities from higher events to lower ones

e) Critical fault clearing time functions

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

V. APPLICATION TO MODEL POWER SYSTEMS

A. Condition of Application

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

(1) A model power system is composed of 3 generators, 11 duplicate lines and 9 buses. Its constitution is shown in Fig.7. The capacities of generators are 247.5, 192 and 128MVA in order of numbers [10].

(2) Only the out of step due to the decrease of transient stability is simulated among fault cascading phenomena. Generators in out of step are isolated from the power system and cause energy loss. The average fault duration time is 1 hour.

(3) Loads have similar change patterns with seasons, date and time

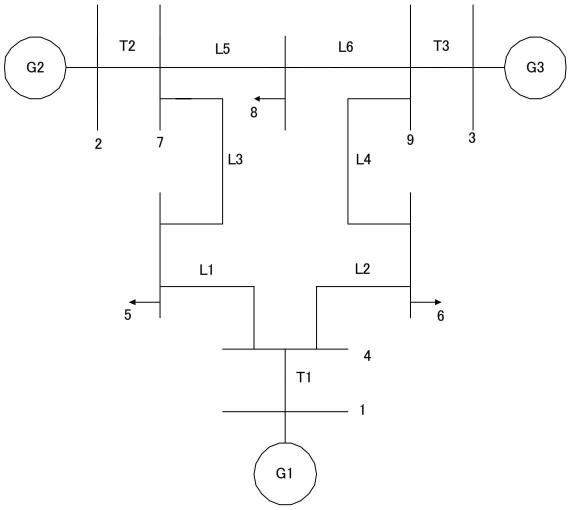

Fig. 7 constitution of model power system

B. Process of Search

Because control systems are the most effective design factors to improve the transient stability and reduce risk of power systems, they are selected as design factors [14]-[17]. In this case, the outline of effect assessment is shown as follows.

(1) Selecting all design factors for detail assessment

Four excitation systems and described later are selected as design factors.

(2) Setting up design factor for detail assessment

The excitation system to be assessed next is set up.

(3) Classifying set up design factor

The excitation system is classified as category 2.

(4) High risk search based on classification

1) Generating probability density functions of loads

The probability density function of load with similar change pattern is shown in Fig.8.

2) Selecting representative faults

Based on heuristic knowledge bases and results of simulation, LLG (two-phase-line-to-line-to-ground-fault) in buses are selected as representative faults.

3) Generating event tree

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.

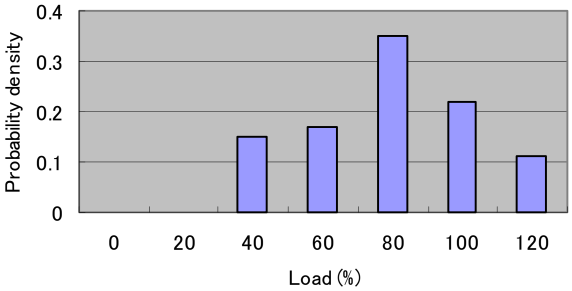

Fig. 8 probability density function of load.

But, the risk will small, for the failure rate of no action is very small [18]. The event tree in case of no action is cut because of the above reason. The generated event tree is shown in Fig. 9.

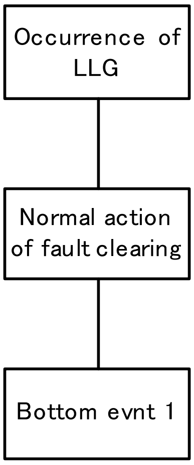

Fig. 9 event tree caused by LLG

4) Selecting representative events

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

a) LLG occurs in buses.

b) Protection systems act normally.

c) Energy loss occurs by loss of transient stability.

5) Calculating risk data in similar load change patterns

a) 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.10. 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.

b) 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. 11. 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.

6) Calculating risk data in non-similar load change patterns

Because it is conditioned that loads have similar change patterns with seasons, date and time, this step is omitted.

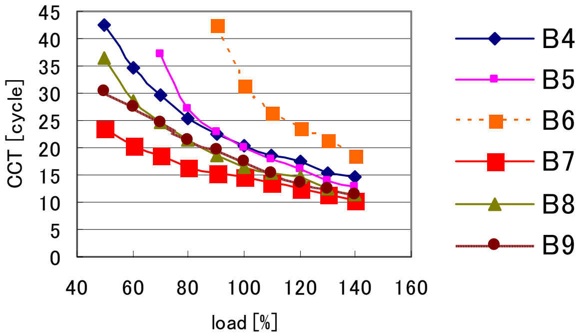

Fig. 10 change of critical fault clearing time functions by fault locations

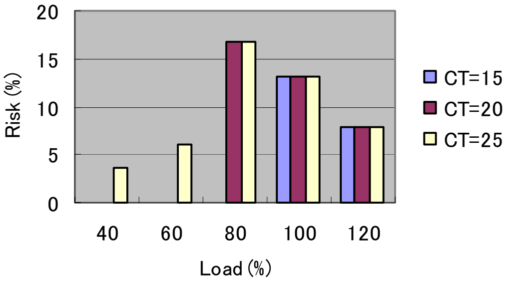

Fig. 11 change of discrete risk functions by CT

7) Identifying high risk events

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

(5) Check of assessing all design factors for detail assessment

If all control systems are assessed, the flowchart is ended. Otherwise, step (2) is processed next and another excitation system is assessed.

The assessed excitation systems are as follows [11], [14].

None : field voltages are held constant at the value consistent with the initial power flow

M1 : model for a continuously acting system with a rotating exciter

M4 : model for older (pre-1967) non-continuously acting excitation system

M9 : model for a special case of model 1, where the generator has a dedicated transformer

The change of critical fault clearing time functions by excitation systems is shown in Fig.12. The unit of time is cycle and one cycle is 0.017 second. This graph makes the following facts clear.

1) CCT decreases monotonously with the increase of load.

2) M1 is the most stable in load smaller than 50% of the rated load.

3) M4 and M9 are very unstable larger than 90% of the rated

load.

The change of CT-Risk functions by excitation systems is shown in Fig.13. When the power loss caused by the fault is the rated load and its duration time is 1 hour, the risk of the concerned fault is relatively expressed as 100%. This graph makes the following facts clear.

1) Risk increases rapidly and monotonously with the increase of CT, but it is saturated in neighborhoods of 30 cycles.

2) The risk of M1 is the lowest.

3) Even if CT is smaller than 20 cycles, the risk of M9 is not zero and the highest. Therefore, M9 should not be adopted in the model power system.

4) Considering synthetically transient stability, control characteristics of the field current in the synchronous machine in order to control its terminal voltage, cost, reliability, life span and so on, adopted exciters should be selected.

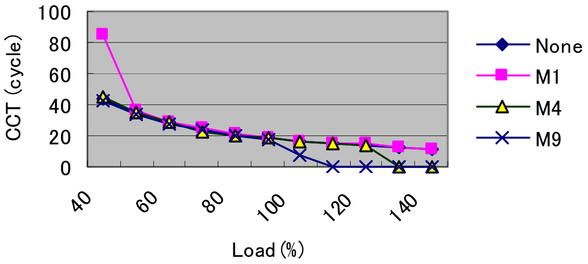

Fig. 12 change of critical fault clearing time functions by excitation systems

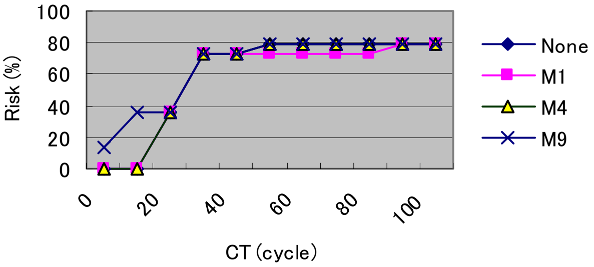

Fig. 13 change of CT-Risk functions by excitation systems

The assessed prime movers are as follows [11], [14].

UMD : user defined model
M 1 : model for a hydraulic turbine
M5 : model for a diesel engine
M6 : model for a gas turbine
M7 : model for a hydraulic turbine
M9 : model for a gas turbine
M10 : model for a simplified turbine) are used

The change of critical fault clearing time functions by prime movers is shown in Fig.14. The unit of time is cycle and one cycle is 0.017 second. This graph makes the following facts clear.

1) The power system is similarly stable in smaller load than the rated one.

2) The power system with the prime mover of model 6 is very unstable in lager load than the rated one.

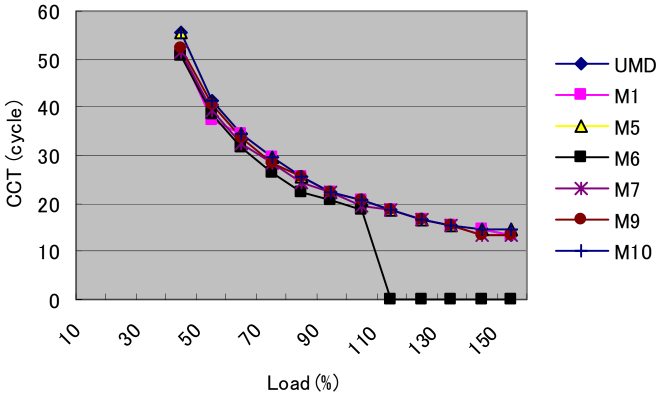

Fig. 14 change of critical fault clearing time functions by prime movers

The change of CT-Risk functions by prime movers is shown in Fig.15. When the power loss caused by the fault is the rated load and its duration time is 1 hour, the risk of the concerned fault is relatively expressed as 100%. This graph makes the following facts clear.

1) Risk increases rapidly and monotonously with the increase of CT, but it is saturated in neighborhoods of 30 cycles.

2) Even if CT is smaller than 10 cycles, the risk of M9 is not zero and the highest. Therefore, M9 should not be adopted in the model power system.

3) Considering synthetically transient stability, control characteristics of mechanical power applied to the generator shaft in order to control the angular speed (frequency), cost, reliability, life span and so on, adopted prime movers should be selected.

C. Results of Application

The results of application have clarified the following facts.

(1) The developed system can assess accurately and efficiently effects of design factors on search for high risk events caused by loss of transient stability of power systems.

(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.

VI. 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 design factors. Results of assessment will improve it.

(2) It will be extended to other fault cascading events except transient stability.

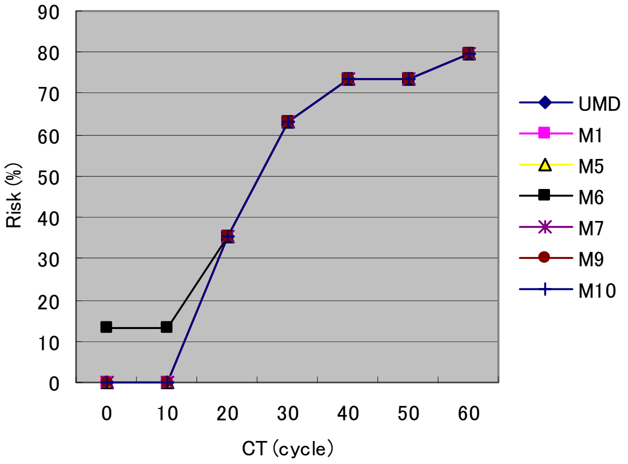

Fig.15 change of CT-Risk functions by prime movers

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