Abstract: We developed formerly the method which can assess the power system transient stability caused by faults using critical fault clearing time functions CCT( W:load ). These functions are knowledge bases which are generated by transforming transient phenomena simulation results of power systems into the form suitable to transient stability assessment. In order to enable to apply it to real power systems, we have developed the new method which can generate efficiently their functions without the increase of assessment errors. The developed method has been applied to the transient stability assessment of model power systems. Results of application have clarified that the developed method has the above ability.


1 Introduction
Transient phenomena cased by faults of power systems are very complex. In order to assess accurately them, simulation methods must be used. But, they have the following problems.
(1) In order to grasp the whole characteristic of transient phenomena, a great number of simulation cases must be carried out.
(2) It is difficult to gain the whole prospects of assessment based on results of individual simulation cases.
(3) When simulation conditions change, simulation must be carried out from the beginning.

We investigated formerly the method to overcome the above problems[1,2]. At first, transient stability which is the most important characteristic to assess in power systems was adopted as the object one and critical fault clearing time functions CCT( W:load ) were newly defined by taking notice of the fact that transient stability is mainly controlled by fault clearing time and load. Next, the method which can generate their functions based on transient phenomena simulation results of power systems was developed. These functions are knowledge bases which are generated by transforming transient phenomena simulation results of power systems into the form suitable to transient stability assessment. Finally, the method which can assess the power system transient stability caused by faults using their functions was developed.

In order to enable to apply it to real power systems which require a great number of simulation cases, it is indispensable to add the ability which can generate efficiently their functions without the increase of assessment errors. Considering this situation, we have newly developed the efficient generation method which adopts the new algorithm generated by using characteristics of their functions. The developed method has been applied to the transient stability assessment of three-phase-to-ground faults in model power systems. Results of application have clarified that the developed method has the above ability.

2 Transient Stability Assessment Method Using Critical Fault Clearing Time Functions

2.1 Outline of Method
The developed method is composed of the following four parts.
(1) decision of assessment fault

(2) generation of critical fault clearing time functions  
(3) calculation of average energy loss of one fault  
(4) calculation of total average power loss of faults

2.2 Decision of Assessment Faults
Transient phenomena case by faults of power systems are variously changed by types, locations, degree of faults. Therefore, the appropriate faults must be set up based on the purpose of assessment. In order to decrease the number of assessment faults without the increase of assessment errors, assessment faults are decided according to the following methods.
(1) Severe faults which cause instability of power systems are preferentially set up.
(2) In case of line faults, faults of representative locations are discretely set up and functions of line fault are generated by interpolating them.

2.3 Generation of Critical Fault Clearing Time Functions

2.3.1 Efficient Generation Method of Functions
The flowchart for generation of critical fault clearing time functions is shown in Fig.1.

The critical fault clearing time CCT is calculated using the bisection algorithm. [ 3 ] The steps of this flowchart are shown as follows.
(1) Setting up load  
The load W is set up.
(2) Setting up 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.
(3) Calculating CT  
The mid-point value CT which is the fault clearing time in the next simulation of transient phenomena is calculated by averaging CT1 and CT2.
(4) Simulating transient phenomena  
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.
(5) 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 the interval is replaced by the mid-point value CT. Otherwise, the upper value CT2 is replaced by the mid-point value CT.
(6) Check of calculation precision

The calculation precision is checked by comparing the difference between CT2 and CT1 with the required precision e. If the difference is smaller than e, then CCT equals to CT1. Otherwise, step (3) is processed next.
(7) 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 shown in 2.3.2 and step (1) is processed next. Otherwise, graphs of CCT functions expressed discretely are made based on CCT data in various loads.

2.3.2 Algorithms for Changing Load
Their functions increase monotonously with the increase of load till the maximum point and decrease monotonously in more load than it. They have both low and high zero points in severe faults. Because the outline form of CCT(W) can be grasped by the above three points, it is important to search efficiently them. Using the above characteristics, loads are set as follows.

1. Low and high zero points are calculated using the method of bisection.
2. If the value of CCT in the middle point is the highest among low, middle and high points, their functions have the maximum value in the maximum point between low and high points. Using this characteristic, 2 points are set in the region where the maximum point will probably exist and the existence region of the maximum point is narrowed more and more by comparing values of CCT until the maximum point is decided.

Flowchart for searching maximum point of critical fault clearing time functions is shown in Fig.2. This flowchart is divided into two parts. The former part searches the state that the value of CCT in the middle point is the highest among low, middle and high points. The latter part searches the maximum point which can satisfy the required precision e. The steps of this flowchart are shown as follows.

- W1, W2 (W1 < W2) are set in the region where the maximum point will probably exist. Next, d=W2-W1, CCT(Wi) (i=1, 2) are calculated.
- CCT(W1) is compared with CCT(W2). If the former is larger than the latter, then next step is processed. Otherwise, step is processed.
- Because the maximum point exists in the lower region than W1, the replacements W1=W1-d,
W2=W1, W3=W2 are carried out. Next, CCT(Wi) (i=1, 2, 3) are calculated. If values of this function have been already known, known values are used without new calculations.

- CCT(W1) is compared with CCT(W2). If the former is larger than the latter, then step ‡B is processed. Otherwise, step ‡H is processed.

- The replacement W3=W2+d is carried out.

- CCT(Wi) (i=1, 2, 3) are calculated. If values of this function have already been known, known values are used without new calculations.

- CCT(W2) is compared with CCT(W3). If the former is larger than the latter, then step ‡H is processed. Otherwise, next step is processed.

- The replacement W1=W2, W2=W3, W3=W3+d are carried out. Next, step ‡E is processed.

- W4=(W1+W2)/2, CCT(W4) are calculated.

- CCT(W4) is compared with CCT(W2). If the former is larger than the latter, then next step is processed. Otherwise, step ‡P is processed.

- The replacement W2=W4, W3=W2 are carried out. Next, next step is processed.

- D= (W3-W2)/2 are calculated. Next, step ‡K is processed.

- W5=(W2+W3)/2, CCT(W) are calculated.

- CCT(W) is compared with CCT(W5). If the former is larger than the latter, then next step is processed. Otherwise, step ‡P is processed.

- The replacement W1=W4, W3=W5 are carried out. Next, step ‡K is processed.

- The replacement W1=W2, W2=W5 are carried out. Next, step ‡K is processed.

- The replacement W1=W2, W2=W5 are carried out. Next, step ‡K is processed.

- The maximum point is compared with the required precision e. If the former is not larger than the latter, then calculations are finished by judging that enough precision has been gained and next step is processed. Otherwise, step ‡P is processed.

- The maximum point is W2 and the maximum values of this function is CCT(W2).

(3) Other loads are preferentially selected in the ranges which have strong non-linearity in this function.

2.4 Calculation of Average Energy Loss of One Fault

At first, the average energy loss due to the out of step in mode m of fault i is calculated as follows. [1]

\[
WTAim = \int_{W_b}^{W_t} PL(W)Cm(W)Rm(W)Tm(W)W dw \quad (1)
\]

Where

- WTAim: average energy loss due to out of step in mode m
- W: load
- Wb: bottom (minimum) value of load
- Wt: top (maximum) value of load
- PL(W): probability density function of load
- Cm(W): function for discriminating occurrence of out of step defined as follows
  \[CCTm(W) - CT > 0 : 0 \text{ (stable)} \]
  \[CCTm(W) - CT \leq 0 : 1 \text{ (unstable)} \]
- CCTm(W): critical fault clearing time function in mode m
- CT: fault clearing time
- Rm(W): ratio of average energy loss in mode m to total average energy in normal state
- Tm(W): average fault duration time in mode m

Next, the average energy loss of assessment fault is calculated as follows.

\[
WTAi = \sum_{m=1}^{mt} WTAim \quad (2)
\]

Where

- WTAi: average energy loss of assessment fault
- mt: total mode number of out of step

2.5 Calculation of Total Average Power Loss of Faults

The total average power loss of faults calculated as follows.

\[
WA = \sum_{i=1}^{it} WTAi \cdot \lambda_i \quad (3)
\]

Where

- WA: total average power loss of assessment faults
- WTAi: average energy loss of assessment fault
- \( \lambda_i \): occurrence rate of assessment fault i
- it: number of faults to be assessed

3 Application to Model Power Systems

3.1 Condition of Assessment

In order to confirm the effectiveness of this method, it was applied to a model power system on the following conditions.
Generators are expressed by the d-q axes model.
(2) Generators are controlled by AVR (automatic voltage regulators) and governors.
(3) Only the tree-phase-to-ground-faults at one node are simulated among faults. It is one of the most severe type faults.
(4) 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.
(5) The probability density function is discretely expressed by 5 sections.

3.2 Assessment of Algorithms for Searching Maximum Point of Critical Fault Clearing Time Functions

The algorithms for searching the maximum point of critical fault clearing time functions was assessed on the following conditions.
(1) A model power system is composed of 5 generators. Its constitution is shown in Fig.3.
(2) A tree-phase-to-ground-fault is occurred at the neighborhood of the node 5.

![Fig.3 Constitution of model power system with 3 generators](image1)

The graph of critical fault clearing time function which is generated by taking loads at intervals of 1% is shown in Fig.4. This function has the maximum value 1.1 at the maximum point 153%. Using algorithms for searching the maximum point, \( n \) (calculation numbers of CCT(W)) required in order to search the maximum point in condition of maximum estimation error 1% are gained, changing both \( e \) (initial estimation error of maximum point) and \( d \) (initial difference from W1 to W2). Both changed variables are calculated as follows.

\[
\begin{align*}
e &= (W1 + W2)/2 - 153 \\
\therefore &= W1 - W2
\end{align*}
\]

The graph which expresses the relationship between \( e \) and \( n \), taking \( d \) as parameter is shown in Fig.5. This graph has clarified the following facts.
(1) The smaller absolute values of \( e \) are, the smaller values of \( n \) are.
(2) When absolute values of \( e \) are small, the smaller values of \( d \) are, the smaller values of \( n \) are.
(3) When absolute values of \( e \) are large, the larger values of \( d \) are, the smaller values of \( n \) are.
(4) When the maximum point is searched by taking from 40% to 230% loads at intervals of 1%, calculation numbers of CCT(W) is 190. The new algorithm is much more efficient than the above method.

![Fig.4 Critical fault clearing time function of model power system with 3 generators](image2)

![Fig.5 Relationship between e (initial estimation errors of maximum point) and n (calculation numbers of CCT(W)), taking d (initial difference from W1 to W2) as parameter](image3)
(5) When it is difficult to estimate the form of CCT(W) beforehand, absolute values of e tend to be large. In this case, the following methods are effective.

- At first, the outline form of CCT(W) is estimated by taking loads at sparse intervals. Next, W1, W2 with small d (initial difference from W1 to W2) is set based on the above information.
- The rather large value of e is set.

### 3.2 Assessment of Transient Stability Assessment Method

In order to confirm the effectiveness of transient stability assessment method, it was applied to a model power system on the following conditions.

1. A model power system is composed of 5 generators.
2. The capacity of one generator is much bigger than those of other generators. The total capacity of other generators is 487MVA.

The change of the average energy loss by fault clearing time is shown in Fig. 6.

![Fig. 6 Change of average energy loss by fault clearing time](image)

This graph makes it clear that the average energy loss increases monotonously with the increase of fault clearing time. The degree of increase is large from 0.2 to 0.5 second, but it is small in more load than it. The above results make it clear that the fault clearing time of the control and protection systems must be smaller than 0.2 second.

### 4 Conclusion

We have developed the efficient generation method of critical fault clearing time functions which adopts the new algorithm generated by using characteristics of their functions. It has been applied to the transient stability assessment of tree-phase-to-ground faults in model power systems. Results of application have clarified the following facts.

1. The developed method can generate efficiently critical fault clearing time functions without the increase of assessment errors.
2. By use of the above functions, the average energy loss and total average power loss can be easily calculated and the effect of control and protection systems on transient stability can be easily and quantitatively assessed.
3. The above functions generated based on transient phenomena simulation results of power systems are knowledge bases which are suitable to transient stability assessment.

We are confident that the developed method will greatly contribute to the improvement of the planning for preventing instability of power systems.

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### References:

