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***Research paper***

# Transient Stability Boundary Assessment Using Rate of Change Kinetic Energy (RACKE) Method for Optimizes Critical Clearing Time

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**Abstract**

In this paper the Rate of Change Kinetic Energy (RACKE) method for multi machine systems was studied and applied to determine of Transient Stability Boundary (TSB) of critically disturbed machine for given contingency. The method has been tested on Iraqi national grid system 400KV. The obtained results were compared by (TSB) assessment based on the Rate of Change Kinetic Energy (RACKE)method with benchmark result (conventional method) through the critical clearing time CCT and the absorbed time for knowing the system case stable or unstable for limiting disturbance conditions. The simulation results show that the method can provide reliable, precise, and quite information about the transient stability boundary.

***Keywords***: *Transient stability, Critical Clearing Time, RACKE Method*

## 1. Introduction

Power system network are equipped with automatic protection devices, with fixed settings, which sense electric faults and clear the faulted sections of the network . One of the main aims of the transient stability analysis is to compute CCT for a given fault conditions. If the time needed by relay equipment to clear the fault is greater than the calculated CCT, the system will lose its synchronism, and some precaution for either adjusting the relay equipment or adjusting system loads and generations, aimed at increasing the system stability margin, is necessary. If the operating time of the relay equipment is shorter than the CCT, the system has some extra stability margin which might allow the operator to rearrange the generation with a view to achieving an optimal and secure dispatch.

In this paper the following situation basically is discussed given initial system operation data and the protection device operating time. The unbalance between the input and output powers may cause instability due to limited margin of transient stability of the system. It is known that TSB has great effect on the CCT. Higher margin of stability leads to a higher of CCT, the question is asked: For a given fault, what increment or decrement in the critical machine's output will make the system marginally stable?

Let Po be the mechanical input power of the critical machine (the sum of input powers in the case of a group of critical machines) during normal operation, and let the input mechanical power, such that the system marginally stable, for a given fault clearing time (with the same system contingency) be P, then TSB is defined as (P – Po) (TSB) is an important concept for dynamic security assessment which quantifies stability margin for power system [10].

It is of interest to know if the output of a given machine can increase and yet operate the system within safe operating limits owing to economic or other reasons .The CCT was calculated in two different ways. The simplified CCT is obtained by the proposed method RACKE and compared with the benchmark CCT* (obtained by conventional method). The error is computed to obtain the validity between them.

To obtain a better estimate of TSB repeat the assessment step, with the result of the confirmation step as the initial data. The algebraic sum of the two assessment of TSB is the corrected TSB .A traditional way of dealing with problem is to run load –flow and transient stability analysis programs alternately, each time making a correction for the mismatch in the assessment CCT and the relay settings, and finally obtained proper operating conditions. This procedure is long and expensive to run unless we have a definite way of modifying the generator output as a function of the mismatch between the CCT and given clearing time. Reference [1] reports a method based on Extended equal area criterion (EEAC).in this paper can be use another method for solution problem power system stability RACKE method .which uses the classical integration up to clearing time and defines a parameter dependent on basic machine parameters, speed and acceleration to indicate stability .nevertheless an index defined as energy margin is indicative of robustness of the power system at a given operating point , the RACKE also provides this indicator for stability.

## 2. Presumption and its validity

The first step in most of the methods for fast transient stability assessment is to form the so- called reduced system [8]. The system reduction process consists in eliminating all the load buses by treating loads as constant impedances and leaving only the generator buses in the system description. Before performing this system reduction, we need to obtain the system operating conditions using the load- flow program.

This means that for every new load or generation, we first need to obtain a valid load –flow and then perform a system reduction. To obtain the TSB, we need to change the generation in small steps and run the transient stability program repeatedly until we arrive at the marginal generation; this is computation –intensive job. If we intend to use the TSB for on-line assistance in system operation, we need a method capable of much faster execution. Towards this end we propose some simplifications are based on careful observations made after simulating numerous faulted power systems.

In a classical modeled [2,3] four and eight generator test are modeled as a constant voltage behind the reactance Xd', load are modelled as constant impedance. The dynamics swing equation for the ith machine of an n- machine system can be represented by the following 2nd –order differential equation:

$$\mathrm{M}\frac{d^2\delta_i}{dt^2} = \mathrm{P}_{mi} - \mathrm{P}_{ei} \quad (1)$$

Most of the direct methods of determining the transient stability are based on the classical model of a power system in the Centre –Of-Angle (COA) or Centre -Of -Inertia (COI) reference frame. In the COA reference frame, machine angle θ is measured with respect to time varying reference axis. In this reference frame, the dynamic eqn (1) can be expressed by the following two Ist-order differential equations [7].

$$\frac{d\theta_i}{dt} = \omega_i \quad (2)$$

$$\mathrm{M}_i\frac{d\omega_i}{dt} = \mathrm{P}_i - \mathrm{P}_{ei} - \frac{\mathrm{M}_i}{\mathrm{M}_T}\mathrm{P}_{COA} \quad (3)$$

For i=1, 2,…..n

$$M_T = \sum_{i=1}^{n} M_i$$

$$\mathrm{P}_{COA} = \sum_{i=1}^{n} P_{COA} - \sum_{i=1}^{n} P'_{gi}$$

For severe faults the first swing of the trajectory of the critical machines is not significantly affected by changes in the critical conditions (of the node voltages and node angles). This is a very important observation. It means that if we have some error in the initial conditions, and then start the numerical integration of the system dynamic (eqns2,3),then the difference between the trajectory generated by this simulation and the simulation starting from exact initial condition is not significant as far as the first swing is concerned. This is owing to the fact that for severe faults, the difference between the input mechanical power and the output electrical power during the fault-on period is so large that the difference in the initial condition turns out to be insignificant compared to the actual machine swing. These comments apply only to the severely disturbed generators; the less disturbed generators which are geographically removed from the fault location, may be substantially affected by the changed initial conditions but then their contribution to the first swing of the critical machines is very small. We make use of the above observations quantitatively as illustrated by various examples in table 1 and 2. Note that the approximation gives valid result even for changes in the critical machines output.

In table 1 and 2 the first row gives the CCT for the given fault condition and the initial conditions which are obtained from the standard load flow. The following row entries are for the modified system operating conditions. To enable a comparison between the proposed method and the conventional method, we calculated the CCT in two different ways and call them the CCT* (the standard method) and the simplified CCT (from the simple method of this paper). Procedures for evaluating CCT* and CCT are given below:

### 2.1. Simplified CCT method:

The simplified CCT, written as CCT, is obtained in the following way.

- Balance the change in generation or loads by assigning the total mismatch between generation and load to the swing bus and leave all the other initial conditions (such as all the node voltages and voltage angles) unchanged, i.e. as given by the initial load flow. For example, if
  ΔPg2=100 MW, ΔPL5¬=50MW
  Then
  ΔPg1= ΔP g2 -ΔPL5=50MW

  Where generator 1 is connected to the swing bus. The voltages behind the transient reactance of the machines affected by this redistribution are set to give their output as the modified power output.
- Form the reduced matrix
- Solve dynamic equations (2), (3) by numerical Step-By–Step integration

### 2.2. Benchmark CCT* method:

The benchmark CCT, written as CCT*, is obtained by following the standard procedure

- Whenever generation or loads change, the load flow program will start by reading the data file
- Form the reduced matrix and start the iterative solving algorithm using fast decoupled method when the program reaches to a solution
- Solve system dynamic equation (2), (3) by numerical Step -By -Step integration.

**Table 1:** Validity Of Presumption For 4– Generator System

| Fault bus | Cleared line | cases | Load flow condition (MW) | CC sec | CCT sec | Error % |
|---|---|---|---|---|---|---|
| 8 | 4-8 | 0 | Initial | | 0.1550 | |
| | | 1 | $\Delta P_{g4}$= 20<br>$\Delta P_{L10}$= 20 | 0.101 | 0.106 | -4.7 |
| | | 2 | $\Delta P_{g4}$= 20<br>$\Delta P_{L9}$= 20 | 0.100 | 0.103 | -2. 9 |
| | | 3 | $\Delta P_{g4}$= 20 | 0.103 | 0.096 | -6.8 |
| | | 4 | $P_{g4}$= 20<br>$P_{L10}$ =$\Delta P_{-L9}$=5 | 0.104 | 0.099 | -4.8 |

**Table 2:** Validity Of Presumption For Iraqi National Supper Gridsystem (400kv)

| Fault bus | Cleared line | cases | Load flow condition (MW) | CCT sec | CCT* sec | Error % |
|---|---|---|---|---|---|---|
| Baiji P.S (1) | Baiji P.S 1 and Hadiytha Dam4 | 0 | Initial | | 0.427 | |
| | | 1 | $\Delta P_{gBAJP}$= 20 $\Delta P_{LKRK4}$= 20 | 0.271 | 0.268 | 1.1 |
| | | 2 | $\Delta P_{gBAJG}$= 20 $\Delta P_{LDAL4}$ =20 | 0.274 | 0.264 | 3.8 |
| | | 3 | $\Delta P_{gBAJP}$= 20 | 0.271 | 0.264 | 2.7 |
| | | 4 | $\Delta P_{gBAJP}$= 20 $\Delta P_{LKRK4}$=20 . $\Delta P_{LDALA4}$=5 | 0.272 | 0.265 | 2.8 |

Table 1and 2 show the effect of making this assumption on tow test system. The tow chosen test system is four generator 11 busbar system (Fig2)[5]and the tow test system Iraqi national network (400KV).The network consideration consists of 22 bus-bar and 35 transmission lines Fig(3)[6]. Only three phase short –circuit fault are simulated in this paper .For each of the faults, three different conditions are simulated

a) Only the commitment of the critical machine is changed.
b) Beside the critical machine, a bus electrically and geographically near the critical machine bus is chosen, at which the load (generation) is increased (decreased).
c) Similar to (b) but a busbar far away from the critical machine busbar is chosen

These tow test situations simulate extreme cases and should provide a good representation of the power system operation.

Observations to note from the results gives in Tables 1and 2 are

1. By comparing the results in the same column in each table, for given fault, the system transient stability (i.e. CCT)is mostly decided by the critical machine`s mechanical input power .Other conditions, such as increasing (decreasing )load and adjusting generation at other buses which in turn will change the distribution profile, make negligible impact. To make this clear Table 1 and 2 have entry average after a set of three different distributions (for a fixed change in critical machine generation) for each fault. In the next section we take this (constancy of the CCT with respect to the excess generation distribution) to be a valid assumption and balance all the excess (deficit) generation of the critical machine with the swing bus only. This means that we do not have to perform the system reduction at every new TSB computation, which results in a considerable saving in computer time.
2. by comparing the results in the same row in each Table, the simplified procedure can give an answer within an acceptable tolerance margin As far as the TSB of the critical machine is concerned, the assumption amounts to this are: if the critical machine's input power is increased (decreased) the slack machine's input power can simply decrease (increase) and let all other machine input powers remain unchanged. According to the test results obtained by the following simple scheme, the CCT was quite accurately able to compute. This assumption is very important in practice because it means that there is no need to recompute the reduced system.

# 3. Transient stability boundary

## 3.1. The RACKE method. [2, 3, 4].

The kinetic energy of the rotating masses of a turbine generator (TG) is

$$\mathbf{W_{ki}} = \frac{1}{2}\mathbf{I_i}\boldsymbol{\omega}_i^2 \quad \text{pu sec} \tag{4}$$

Where

Ii is the TG moment of inertia in pu sec of machine i And ωi is the TG angular velocity in rad sec of machine i

$$W_{kis} = \frac{1}{2} I_i \omega_s^2 \quad \text{pu sec} \tag{5}$$

$= H_i$ Where, Hi is the inertia constant of machine I

Or $H_i = \frac{1}{2} I_i \omega_i^2$ sec

Or $I_i = 2H_i\omega_s^2$ (6)

Times speed angular momentum of machine i may be defined by [4].

$$M_i = I_i\omega_s \quad \text{pu sec}^2\text{/rad} \tag{7}$$

Hence it is customary when solving the swing equation to regard ,$M_i$ as constant and that is the value of angular momentum at synchronous speed.

Now the rate of change of kinetic energy is given by taking the derivate of equation (4) we have

$$\frac{dW_{ki}}{dt} = \frac{1}{2} I_i \left(2\omega_s \frac{d\omega_s}{dt}\right)$$

$$\triangleq P_{ki}$$

$$P_{ki} = I_i\omega_i \frac{d\omega_i}{dt}$$

$$P_{ki} = M_i \left(\frac{\omega_i}{\omega_s}\right)\frac{d\omega_i}{dt} \tag{8}$$

Substituting equation (1) into equation (8) gives

$$P_{ki} = \frac{\omega_i}{\omega_s}(P_{mi} - P_{ei}) \tag{9}$$

At fault clearance, using the post fault network configuration, then $P_{ki}$ or $(RACKE)_i$ is given by

$$(RACKE)_i = \omega_{ie}(P_{mi} - P_{ei}) \tag{10}$$

Where $\omega_{is}$ is the rotor speed at fault clearance. In other words the $(RACKE)_i$ in equation (10) has negative maximum at the critical clearing time .

## 3.2. Assessment of TSB

Now let us consider how to assessment the TSB using rate of change kinetic energy for a multi-machine system. Suppose the fault applied at the generator terminals, causes the power output to be zero during the period of the fault then equation (1) will be:

$$M\frac{d^2\delta}{dt^2} = P_{mi} \tag{11}$$

Equation (11) can be solved for δ as a function of time. The solution is as follows:

$$\int_{to}^{tu} \frac{d^2\delta}{dt^2} = \int_{to}^{tu} \left(\frac{P_{mi}}{M}\right) dt$$

$$\int_{to}^{tu} \frac{d^2\delta}{dt^2} dt = \int_{to}^{tu} \frac{P_{mi}}{M} dt$$

$$\text{Or} \quad \frac{d\delta}{dt} = \left(\frac{P_{mi}}{M}\right) t \tag{12}$$

$$\text{Then} \quad \int_{to}^{tu} \frac{d\delta}{dt} dt = \int_{to}^{tu} \left(\frac{P_{mi}}{M}\right) t dt$$

$$\int_{\delta_o}^{\delta_u} d\delta = \frac{Pmi}{M}\frac{1}{2}t^2|_{t_o}^{t_u}$$

$$\delta_{t_u} - \delta_{t_o} = \left(\frac{P_{mi}}{2M}\right)t_u^2$$

$$\delta_{t_u} = \delta_{t_o} + \frac{P_{mi}}{2M}t_u^2 \quad (13)$$

$t_u = t_c$ then $\delta_{tc}$ will be $\delta_c$

$$\delta_c = \delta_o + \frac{P_{mi}}{2M}t_c^2 \quad (14)$$

Equation (1) can be written as follow

$$\frac{d^2\delta}{dt^2} = \frac{P_{mi}}{M} - \frac{P_{max}}{M}\, sin\delta_c \quad (15)$$

Suppose the ith machine original mechanical input power is $P^o_{mi}$ and the given contingency the critical clearing angle is $\delta^c_i$ .Let us assume that when the input power increased to $P_{mi}$ ,the critical clearing angle is $\delta^t_i$ ,with the same contingency. The equation (15) became.

$$\Delta P_{mi} = P_{mi} - P^o_{mi}$$

$$\frac{d^2\delta}{dt^2} = \frac{\Delta P_{mi}}{M} - \frac{P_{max}}{M}\, sin\delta_c \quad (16)$$

Substituting for $\delta_c$ using (16)

$$\frac{d^2\delta}{dt^2} = \frac{\Delta P_{mi}}{M} - \frac{P_{max}}{M}\, sin\left(\delta_o + \frac{P_{mi}}{2M}t_c^2\right) \quad (17)$$

Equation (8) can be written as follow:

$$RACKE = M_i\left(\frac{\omega_i}{\omega_s}\right)\frac{d\omega_i}{dt}$$

$$RACKE = M_i\left(\frac{d\delta(t)}{dt}\right)\frac{d^2\delta}{dt^2}$$

Now substitute for both $\left(\frac{d\delta}{dt}\right)$ and ( $\frac{d^2\delta}{dt^2}$) using equation (12) and (17) Respectively. We have.

$$RACKE(t_c) = \frac{M}{\omega_S}\frac{P_m}{M}t_c\left[\frac{\Delta P_{mi}}{M} - \frac{P_{max}}{M}\sin\left(\delta_O - \frac{P_m}{2M}t_c^2\right)\right]$$

$$RACKE(t_c) = \frac{P_m}{M\omega_s}t_c\left[\Delta P_{mi} - P_{max}\sin\left(\delta_O - \frac{P_m}{2M}t_c^2\right)\right]$$

$$RACKE(t_c) = \frac{P_m\Delta P_{mi}}{M\omega_s}t_c - \frac{P_mP_{max}}{M\omega_s}\sin\left(\delta_O - \frac{P_m}{2M}t_c^2\right)$$

Let $\delta_1(t) = \delta_o + \frac{P_{mi}}{2M}t^2$

$$\left.\frac{d_{\delta_1}(t)}{dt}\right|_{t=t_c} = \left(\frac{P_m}{M}\right)t \qquad ; \qquad \left.\frac{d^2{}_{\delta_1}(t)}{dt^2}\right|_{t=t_c} = \left(\frac{P_m}{M}\right)$$

$$RACKE(t_c) = \frac{P_m\Delta P_{mi}}{M\omega_s}t_c - \frac{P_mP_{max}}{M\omega_s}t\sin(\delta_1) \quad (18)$$

$$\Delta P_{mi} = RACKE(t_c) - (\frac{P_mP_{max}}{M\omega_s}t\sin(\delta_1))M\omega_S/P_mt_c \quad (19)$$

$\Delta P_{mi}$ Is assessment of TSB of the critical machine i, for clearing time t, practically, the value

$$\Delta P^*_{mi} = \Delta P_{mi}\left(1 - \frac{M_i}{M_T}\right)^{-2} \quad (20)$$

Gives a better assessment.

If t > $t_c$, there is no information about $\delta_i^{tl}$ from the original fault trajectory. The extrapolation method or Taylor series method is suggested for calculating $\delta_i^{tl}$ using three point extrapolation formulas, can be choose three different points $\delta_i^t(t_1)$ , $\delta_i^t(t_2)$ , $\delta_i^t(t_3)$ where ($0 \le t_1 \le t_2 \le t_3 \le t_c$ )are available from the original trajectory and computed $\delta_i^{tl}$ as

$$\delta_i^{tl} = \frac{(t-t_2)(t-t_3)}{(t_1-t_2)(t_1-t_3)}\delta_i^t(t_1) + \frac{(t-t_1)(t-t_3)}{(t_2-t_1)(t_2-t_3)}\delta_i^t(t_2) + \frac{(t-t_1)(t-t_2)}{(t_3-t_1)(t_3-t_2)}\delta_i^t(t_3)$$

### 3.3. Determination of TSB

Basically three steps are involved in the determination of TSB.

- Assessment**:** assess the TSB ($\Delta P_{mi}$) using equation (19) and (20) for given CCT (in practice, it might be a fault – clearing time set by a protection device).
- Confirmation: Modify the mechanical input of the critical machines, by adding the TSB assessment by previous step and balance the system generation and load by assigning the net mismatch to the slack machine. These modified values of the generation are taken as prefault balanced load flow data. Then the transient stability program is run, using the original reduced system and the modification as suggested by step (1), to obtain a CCT which is the first assessment CCT.
- Correction**:** Usually the CCT first assessment by the previous confirmation step is different from the expected CCT. Repeat the assessment step, with the results of the confirmation step as the initial data, to obtain a better estimate of TSB. The algebraic sum of the two assessment $TSB_s$ is the corrected TSB.

## 4. Applications and results

The above three steps on tow test system has been chosen and applied as follows:

### 4.1. Test system S1

The first multi machine test system is a four machine ten bus bar [9].A three phase to ground is applied on line (2-6) near node 6 After fault clearance, the circuit breaker at both end of line (2-6) was opened. According to the (SBS) numerical integration, the system is stable when CCT=0.1449sec. The system is unstable when CCT= 0.1450sec. According to RACKE, the following "candidate" CCTi's is given: Gi: CCT1=0.1550 sec; CCT2 =0.1456sec; CCT3 =0.220, CCT4= 0.210s, Hence according to the RACKE, the CCT is 0.1456sec, and the critical generator is G2. Applying the three phase fault in the same position, causes a change in mechanical input power for the same machine (generator 2). To assess the ΔPmi, as mentioned in section 3 and the results the three steps are followed as shown in table (3).

### 4.2. Test system S2

The second multi-machine test system is a Iraqi National supper Grid system (400KV) [6]. The disturbance initiating the transient is a three phase fault occurs in line between Baiji P.S(1) and Haditha Dam(4) near bus Baiji P.S(1), the fault is cleared by opening of the circuit breakers at both ends of the line According to the (SBS) numerical integration, the system is stable when the fault clearing time is 0.427sec., and the system is unstable when the fault clearing time is 0.429sec

According to RACKE, the following "candidate" $CCT_i$'s is given :$G_i$: $CCT_{BAJG}$ =0.455 sec; $CCT_{BAJP}$ =0.425sec; $CCT_{HDTH}$ =0.467, $CCT_{MUSP}$ = 0.55, Hence according to the EEAC, the CCT is 0.0.425sec and the critical the critical machines is Baiji P.S. Applying the three phase fault in the same position ,causes a change in mechanical input power for the same machines (Baiji P.S) .To assess the $\Delta P_{mi}$ ,the three steps are followed as mentioned in section 3 and the results as shown in table(4).

## 5. Results Discussion

In this Section, we present the results performed on the tow test systems, various contingencies on these system have been studied. For each of cases we choose the expected CCTs such that some larger than the initial CCT. To see how well the first step (assessment) works and to compare the assessment and correction we list in tables (3- 6). In all cases the simplified CCT and benchmark CCT*are calculated for all the contingencies to test the method for evaluating the TSB.

The error percentage is computed by

$$\%error = \frac{(ExpectedCCT) - (CCT^*)}{(ExpectedCCT)} \times 100$$

**Table 4:** Tsb Assessment For The 4-Machine System Initial Data: Fault Bus (6), Cleared Line (2-6), Original Cct*(0.1449 Sec) Critical Machine (2) And Its Original Power Input (7.000p.)

| | First assessment | | | | Corrected assessment | | | |
|---|---|---|---|---|---|---|---|---|
| **Expected CCT (sec)** | **TSB p.u** | **CCT Sec** | **CCT* Sec** | **Error (%)** | **TSB p.u** | **CCT Sec** | **CCT* Sec** | **Error (%)** |
| 0.100 | 0.72 | 0.102 | 0.105 | 5.0 | 0.89 | 0.100 | 0.105 | 5.0 |
| 0.150 | -0.80 | 0.147 | 0.147 | -2.0 | -0.88 | 0.150 | 0.149 | -0.7 |
| 0.200 | -0.25 | 0.202 | 0.203 | 1.5 | -0.23 | 0.201 | 0.202 | 1.0 |
| 0.250 | -0.201 | 0.252 | 0.254 | 1.6 | -0.21 | 0.252 | 0.253 | 0.8 |

**Table 4:** TSB assessment for the system a Iraqi National supper Grid system (400KV)

| | First assessment | | | | Corrected assessment | | | |
|---|---|---|---|---|---|---|---|---|
| **Expected CCT (sec)** | **TSB p.u** | **CCT Sec** | **CCT* Sec** | **Error (%)** | **TSB p.u** | **CCT Sec** | **CCT* Sec** | **Error (%)** |
| 0.100 | 0.72 | 0.102 | 0.105 | 5.0 | 0.89 | 0.100 | 0.105 | 5.0 |
| 0.150 | -0.80 | 0.147 | 0.147 | -2.0 | -0.88 | 0.150 | 0.149 | -0.7 |
| 0.200 | -0.25 | 0.202 | 0.203 | 1.5 | -0.23 | 0.201 | 0.202 | 1.0 |
| 0.250 | -0.201 | 0.252 | 0.254 | 1.6 | -0.21 | 0.252 | 0.253 | 0.8 |

Initial data: three phase fault occurs in line between Baiji P.S(1) and Hadiytha Dam(4) near bus Baiji P.S(1), original $CCT^*$=0.427sec the critical machine is Baiji G.P.S and its original power input (2.00 p.u)

## 6. Conclusion

The RACKE concept is extended to be applied for multi-machine power system. A method is suggested for providing an equivalent system to the multi-machine system using reduction techniques and combining machines. The equivalent system is a single machine connected to a dynamic infinite bus so that an initial critical clearing time can be assessed. This method is similar to the determination of first-swing stability except that there is no need to form the reduced system repeatedly. The reason for not having to form the reduced system again is that within certain limits, the system transient stability (i.e., CCT) mostly depends upon the mechanical input of the critical machines, and other condition make very difference to the CCT.The RACKE method is limited by the accuracy of its models and the statistic shows the error can basically keep below 20%; the hybrid method mentioned in this paper can combine the merits of the RACKE method (fast speed) and the time-domain simulation method (high accuracy), and simulation results demonstrate that it is more competent in online application.

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