



## Prediction of Critical Clearing Time of Java-Bali 500 kv Power System Under Multiple Bus Load Changes Using Neural Network Based Transient Stability Model

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**Abstract:** A transient stability model based on back propagation neural network is used to analyze transient stability of Java-Bali electricity system, especially in calculating the critical clearing time. The real and the active load changes on each bus that shows the real load pattern of the system used as neural network input, while the target is the Critical Clearing Time (CCT). By using the load pattern as input, it is hoped that the robustness of the proposed method against load changes at multiple bus can be achieved. Data of target critical clearing time used for the training was calculated from the concept of One Machine Infinite Bus (OMIB), by reducing the multi-machine system using a combination of methods of Equal Area Criterion (EAC) through the Trapezoidal method and the Runge-Kutta 4th order method. To analyze transient stability, a three phase ground fault was conducted at one bus and assumed not changed during the simulation. The proposed method will be implemented at Java-Bali 500 kv power system. The simulation results show the calculation of critical clearing time from the proposed method has a minimum error of 0.0016% and a maximum error of 0.0419% compared with CCT by OMIB.

**Keywords:** transient stability, multimachine, one machine infinite bus, equal area criterion, neural network, critical clearing time.

### 1. Introduction

In recent years, research on the transient stability problem revolves around the identification of critical machine, critical clearing time and system transient stability modelling. However, solving non linear calculations on transient stability requires a long time, in contrast with the necessity to overcome the problem quickly and accurately [1].

A transient stability study with random variables is performed in [2], with linear approach involving the calculation of sensitivity derived from the CCT system. The study uses a complex reduction equation to determine the possibility of the system experiencing transient conditions. Determination of conditions of transient stability using multilayer perceptron artificial neural network studied in [3]. However, some weakness occurred in the determination of transient conditions of the system grouped by high and low class such that it did not accurately give a prediction value of CCT

Recent issues on the transient stability are how to calculate the CCT quickly and accurately, and has been approached using artificial intelligent, especially neural network because it can be applied online. Using neural networks the non linear characteristic of the system can be modelled easily. The advantages of using artificial neural network is a quick identification

process, high accuracy and can solve non linearity problem [8]. Changes in the dynamic condition of the system can be modelled easily by neural network and therefore the robustness of the method based on neural network against load changes at multiple bus is guaranteed. In addition, the result of training of the neural network can applied on line, so that the condition of transient stability of the system is able to be known in a short time.

Critical clearing time prediction using neural networks has been published in many papers. Reference [9] determine the critical clearing time with the fault distance as an input applied on a single machine system using neural network. In this paper, neural network is able to assess the stability of the system with accurate transient for symmetric fault along the line. Some papers on critical clearing time related with a contingency on the system have been published at [10,11,12]. Reference [10] presented a neural network based approach for online implementation through estimation of a normalized transient stability margin for a particular contingency under different operating conditions. This method with a time-domain simulation technique is used to obtain the training set of the neural network. Reference [11] describes the procedures for reasoning CCT by means of rules extracted from a multilayer perceptron (MLP) artificial neural network. However, this reference still has weaknesses, the lack of consistency in force. Reference [12] discuss about prediction of CCT on the system caused by a fault on a bus from the generator. Some improvement could be achieved by increasing the number of hidden neurons and the number of training examples.

This study is trying to implement back propagation neural network to calculate critical clearing time of the system transient stability. The real and the active load changes on each bus that shows the real load pattern of the system used as neural network input, while the target is the Critical Clearing Time (CCT). By using the load pattern as input, it is hoped that the robustness of the proposed method against load changes at multiple bus can be achieved. Data of target critical clearing time used for the training was calculated from the concept of One Machine Infinite Bus (OMIB), by reducing the multi-machine system using a combination of methods of Equal Area Criterion (EAC) through the Trapezoidal method and the Runge-Kutta 4th order method. To guarantee the robustness of the proposed method against load changes in multiple bus, several certain load patterns are chosen to calculate the critical clearing time. It is expected that calculations can be carried out online and in less amount of time.

## **2. Methodology**

### *A. General Methodology*

The general methodology can be seen in figure 1. It starts from reading the data. The necessary data are power system network, data of generators, and load data. All this data is required for power flow studies to determine the voltage and phase angle and the loading of each bus before the disturbance. So, the performance of initial system was knowable.

The next step is the modelling of transient stability. Modelling machines for transient stability condition is done by giving three phase short circuit on one bus. The Severely Disturbed Machine can be determined by observing the acceleration of the machine when the disturbance is happened.

It is necessary to reduce the modelling machine into one machine, because it can simplify to solve problems, and then classify the machines into two groups, the critical machine and non critical machine. Two machines groups, then, is reduced into one machine infinite bus and the Critical Clearing Time can be calculated with a combination of OMIB equal area criterion via the trapezoidal method and the 4<sup>th</sup> Order Runge Kutta method.

Neural Network (NN) is trained using CCT of OMIB-EAC obtained from the previous step. After training, the NN model will be tested using new operation condition to compute CCT. The results of testing CCT-NN will be compared with CCT-OMIB-EAC.

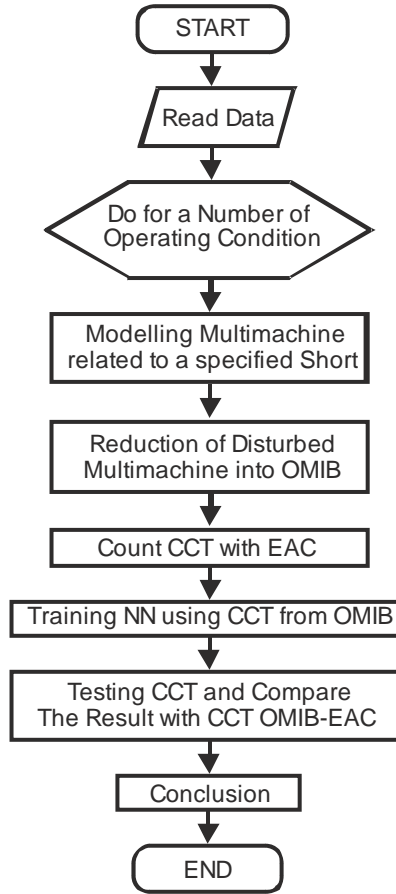


Figure 1. Determination Flowchart of CCT

## B. Detail Methodology

### B.1. Modelling Multimachine for Transient Stability

Transient stability in power systems is the system's ability to maintain operating conditions when large disturbances occur. Disturbance in the system can cause major changes in the angle rotor and systems. Failure to manage the interference will result in loss of synchronization between machines. Machine stability limit is different from one another.

By looking at the stability limit of the worst machines, then the system transient stability can be determined. Machines that have the lowest stability limit is the most critical machine that has a tendency to initiate instability and loss of synchronization on the system. As a result, other machines will be affected and lose synchronization also form a group of machines that are not stable in the system. Mathematical modelling of machine dynamics state- $i$  with reference to the COA (Centre of Angle) is written as follows [7],

$$\frac{d\delta_i}{dt} = \omega_i \quad (1)$$

$$M_i \frac{d\omega_i}{dt} = P_i - P_{ei} - \frac{M_i}{M_T} \quad (2)$$

$$P_i = P_{mi} - E_i^2 G_{ii}$$

$$P_{ei} = \sum_{j=1}^n (C_{ij} \sin \delta_{ij} + D_{ij} \cos \delta_{ij})$$

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

where,

$$C_{ij} = E_i E_j B_{ij}$$

$$D_{ij} = E_i E_j G_{ij}$$

$E_i$  = internal voltage generator

$\delta_i$  = rotor angle

$$\delta_{ij} = \delta_i - \delta_j$$

$\omega_i$  = velocity

$P_{mi}$  = prime mover

$M_i$  = inertia constant

$B_{ij}$  = conductance (of the matrix impedance already reduced)

$G_{ij}$  = susceptance (of the matrix impedance already reduced)

The right hand side of equation (2) is called acceleration power machine ( $P_{ai}$ ).

$$P_{ai} = P_i - P_{ei} - \frac{M_i}{M_T} P_{COA} \quad (3)$$

By eliminating the free variable  $t$  in equations 1 and 2, the differential equations between  $\delta_i$  and  $\omega_i$  can be written as follows,

$$M_i \omega_i d\omega_i = P_{ai} d\delta_i \quad (4)$$

## 2. Reducing into One Machine Infinite Bus (OMIB)

Conventional methods of analyzing the stability have some weakness such as computing time is longer, lack of information about the sensitivity and control. To cover the weakness above, researchers developed several methods such as Lyapunov in the early 1960s. Then the method of EAC (Equal Area Criterion) which was updated in 1980, with multi-machine system is converted into One Machine Infinite Bus (OMIB).

In this research, a better method decomposing the multimachine system into two machine and then combined two machines into One Machine Infinite Bus (OMIB) will be used. This method will generally divide the generators into two groups, namely group of critical machines (generators are responsible for the loss of synchronization) and non-critical group of generators (power remaining) and finally combined both resulted groups into one machine to infinite bus. Several stages of this method is as follows,

1. Perform short circuit simulation to obtain the stability condition of machinery and machine grouping into two groups namely the critical machines and non-critical machines
2. Modeling group of critical machines into one machine model and non-critical machines into one machine model also
3. Two models of machines were reduced back to one model of machine to infinite bus.

The method to divide the multimachines into two groups is based on machine acceleration power looked at the post fault condition. Machine  $i$  can be categorized into one of the Severe Disturbed Machine (SDM) group if it satisfies the following equation

$$\frac{|a_i^f|}{a_{\max}^f} > a \quad (5)$$

$a_i^f$  is the acceleration of the  $i$ -th machine at the time of disturbance,  $a_{\max}^f$  is the maximum acceleration value of machinery and  $a$  is the tolerance allowed (the value of 0.7 is sufficient to



arches curve of the function  $f(x)$  is replaced by a straight line. As shown in Figure 3 the area under the function  $f(x)$  between  $x = a$  and  $x = b$  is approached by a trapezoidal area formed by straight lines connecting the  $f(a)$  and  $f(b)$  and the  $x$ -axis and between  $x = a$  and  $x = b$ . Approach is done with one parts (trapezoidal). According to the formula geometry, area trapezoid is [16]:

$$I \approx (b - a) \frac{f(a)+f(b)}{2} \tag{15}$$

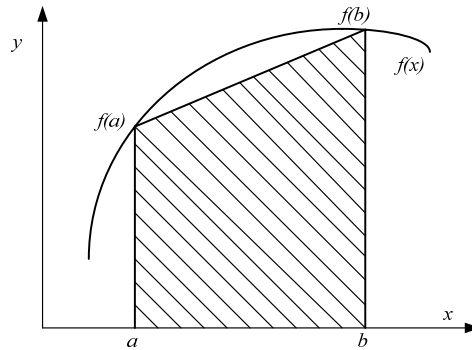


Figure 3. Trapezoidal Method

As shown in figure 3, the use of straight lines to approximate the curved lines caused the error of area that are not shaded. The amount of errors that occur can be estimated from the following equation:

$$E = -\frac{1}{12} f''(\epsilon)(b - a) \tag{16}$$

with  $\epsilon$  is a point which is located in the interval  $a$  and  $b$ . The equation above shows that if the integrated function is linear, then the trapezoid method will give exact values for the second derivative of the linear function is zero. Instead for the function with the degree of two or more, using the trapezoidal method will give an error.

Trapezoidal method is used to determine the critical angle ( $\delta_{cr}$ ) of the equivalent OMIB generator. In this method, to minimize error the curve is approached by a number of straight lines, form in many layers as in Figure 4.

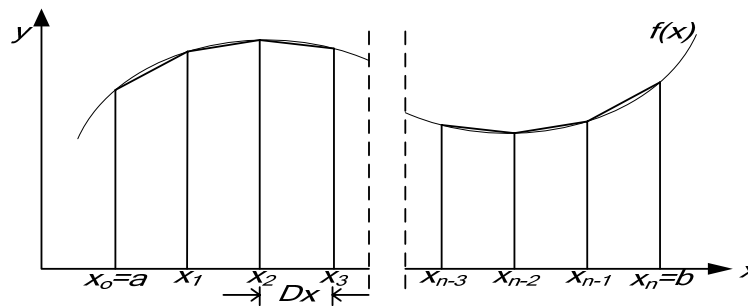


Figure 4. Trapezoidal Method with Many Layers

Total area is the sum of the layers area. The smaller divisions of the trapezoid area, more accurate results are obtained. If there are  $n$  layers, mean of layers is:

$$\Delta x = \frac{b - a}{n} \tag{17}$$



When the disturbance is removed at the point of  $\delta_c$ , which shifts the operating point to the initial power angle curve at point  $e$ . Net power is now declining, and its kinetic energy will reach a zero value at the point  $f$ , when the shaded area ( $defg$ ), characterized by  $A_2$ , same with the shaded area ( $abcd$ ), characterized by  $A_1$ . Since  $P_e$  is greater than  $P_m$ , the rotor will continue to slow in line-power angle curve past the point of  $e$  and  $a$ . Because the effects of damping, the oscillations slowed and the operating point back to the point of initial power angle  $\delta_0$ . So the equation will be obtained for termination of the critical angle is achieved if the increase  $\delta_l$  cause the area  $A_1$ , which shows the deceleration area, smaller than the area that shows the acceleration energy. This occurs when  $\delta_{max}$ , or point of  $f$ , is at an intersection between the lines  $P_m$  and curves  $P_e$ , as shown in Figure 3. By using the equal area criteria, it was found,

$$\int_{\delta_o}^{\delta_c} P_m d\delta = \int_{\delta_c}^{\delta_{max}} (P_{max} \sin \delta - P_m) d\delta \quad (28)$$

be integrated equation, then obtained,

$$P_m (\delta_c - \delta_o) = P_{max} (\cos \delta_c - \cos \delta_{max}) - P_m (\delta_{max} - \delta_c)$$

$$\cos \delta_c = \frac{P_m}{P_{max}} (\delta_{max} - \delta_o) + \cos \delta_{max} \quad (29)$$

#### B. The 4<sup>th</sup> RUNGE KUTTA

The 4<sup>th</sup> Order Runge Kutta is used to determine the critical clearing time ( $t^{cr}$ ) of OMIB based on  $\delta_c$  which has been established in previous processes. To determine the value of  $x_t$  using 4<sup>th</sup> Order Runge Kutta first, determine the following four constants [16],

$$k_1 = f(t_i, x_i) \Delta t \quad (30)$$

$$k_2 = f(t_i + (0.5)\Delta t, x_i + (0.5)k_1) \Delta t \quad (31)$$

$$k_3 = f(t_i + (0.5)\Delta t, x_i + (0.5)k_2) \Delta t \quad (32)$$

$$k_4 = f(t_i + \Delta t, x_i + k_3) \Delta t \quad (33)$$

then the value of  $x$  can be determined as follows:

$$x_{i+1} = x_i + (1/6) * (k_1 + 2k_2 + 2k_3 + k_4)$$

When applied to find the critical clearing time ( $t_{cr}$ ) are as follows:

$$k_1 = f(\delta_i, \omega_i) \Delta t = \omega_i \Delta t$$

$$l_1 = g(\delta_i, \omega_i) \Delta t = (\pi f / H_i) * P_a^f(\delta_i) * \Delta t$$

$$k_2 = f(\delta_i + 0.5k_1, \omega_i + 0.5l_1) \Delta t = (\omega_i + 0.5l_1) * \Delta t$$

$$l_2 = g(\delta_i + 0.5k_1, \omega_i + 0.5l_1) \Delta t = (\pi f / H_i) * P_a^f(\delta_i + 0.5k_1) * \Delta t$$

$$k_3 = f(\delta_i + 0.5k_2, \omega_i + 0.5l_2) \Delta t = (\omega_i + 0.5l_2) * \Delta t$$

$$l_3 = g(\delta_i + 0.5k_2, \omega_i + 0.5l_2) \Delta t = (\pi f / H_i) * P_a^f(\delta_i + 0.5k_2) * \Delta t$$

$$k_4 = f(\delta_i + k_3, \omega_i + l_3) \Delta t = (\omega_i + l_3) * \Delta t$$

$$l_4 = g(\delta_i + k_3, \omega_i + l_3) \Delta t = (\pi f / H_i) * P_a^f(\delta_i + k_3) * \Delta t$$

then, the value of  $\delta$  and  $\omega$  is,

$$\delta_{i+1} = \delta_i + (1/6) * (k_1 + 2k_2 + 2k_3 + k_4)$$

$$\omega_{i+1} = \omega_i + (1/6) * (l_1 + 2l_2 + 2l_3 + l_4)$$

where,  $\delta_1 = \delta^0$  and  $\omega_1 = 0$

By increasing  $t$  from 0 to 1 second using a small  $\Delta t$  it will be found CCT ( $t^{cr}$ ). Iteration will stop if  $\delta_n = \delta^{max}$





### 3. Implementation

The system used in this study is the Java-Bali interconnection 500kV. This system consists of 23 buses with 28 mesh transmission and 8 generators as can be seen in figure 7.

The generators are Suralaya, Muaratawar, Cirata, Saguling, Tanjungjati, Gresik, Paiton, and Grati. Among these eight plants, power plants Saguling Cirata are water power plants, while others are steam power plants. In this study Suralaya power plant act as a slack generator. The load data obtained from PT PLN (Persero) [17]. The kV base is 500 kV, MVA base is 1000 MVA, and the system frequency is 50 Hz. Generator data used are shown in Tables 1.

Table . Generator Data

Generator Number	Generator Name	$X_d'$ (pu)	H
1	Suralaya	0.297	5.19
2	Muaratawar	0.297	1.82
3	Cirata	0.274	2.86
4	Saguling	0.302	1.64
5	Tanjung Jati	0.2588	3.2
6	Gresik	0.297	2.54
7	Paiton	0.297	4.42
8	Grati	0.297	3.5

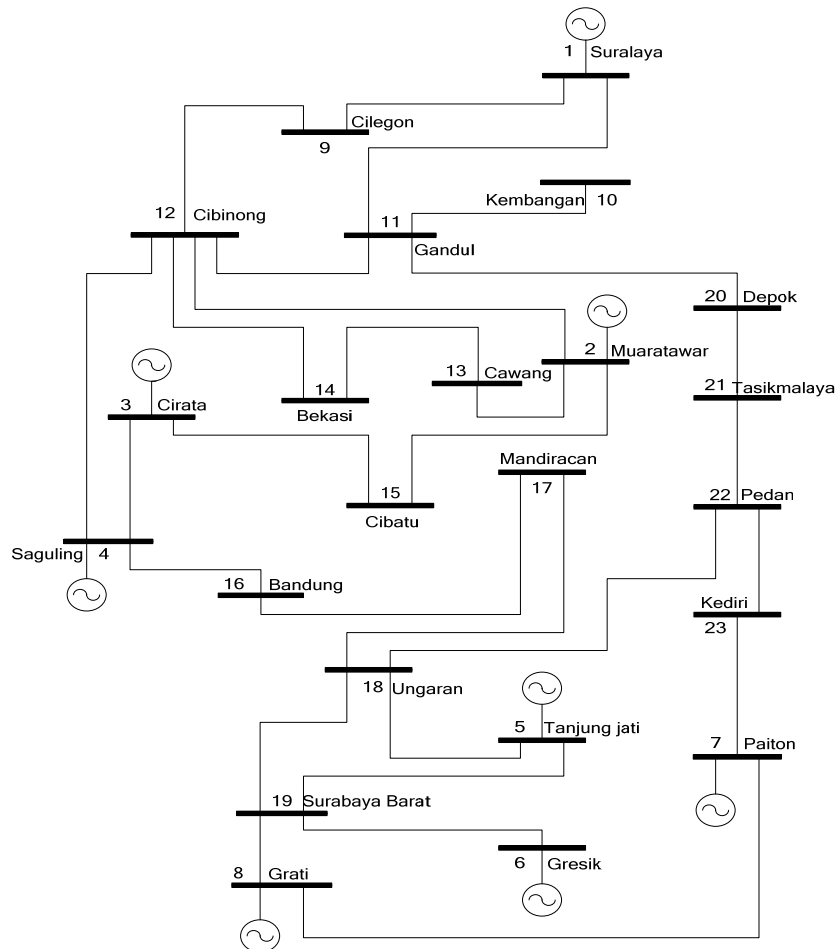


Figure 7. Diagram of the Java-Bali Interconnection System Lines 500 kV



Table 3. Comparison Training CCT using OMIB-EAC and Neural Network Method

NO	TIME	TRAINING CCT	CCT OMIB-EAC	ERROR
		(s)	(s)	(%)
1	18:00	0.2801	0.2800	0.0002
2	18:15	0.2839	0.2840	0.0004
3	18:30	0.2882	0.2880	0.0005
4	18:45	0.2848	0.2850	0.0005
5	19:00	0.2826	0.2820	0.0020
6	19:15	0.2869	0.2880	0.0037
7	19:30	0.2866	0.2860	0.0021
8	20:00	0.2820	0.2840	0.0002
9	20:15	0.2870	0.2870	0.0000
10	20:45	0.2779	0.2780	0.0003
11	21:00	0.2750	0.2750	0.0002
12	21:15	0.2711	0.2710	0.0004
13	21:30	0.2680	0.2680	0.0001
14	21:45	0.2640	0.2640	0.0000
15	22:00	0.2570	0.2570	0.0000
16	22:15	0.2550	0.2550	0.0000
17	22:30	0.2530	0.2530	0.0000
18	22:45	0.2470	0.2470	0.0000

From training result, we obtain that the minimum error was 0%, and maximum error is 0.0084%. The average error of neural network training to OMIB-EAC method is 0.0005186. The comparison accuracy of the output value of the CCT using the method OMIB-EAC and Neural Network can be seen in Figure 8.

Table 4. CCT OMIB-EAC For Testing NN

TIME	BUS NUMBER						CCT OMIB-EAC (s)
	9		10		11		
	MW	MVAR	MW	MVAR	MW	MVAR	
00:45	337	208	198	122	326	202	0.2220
04:15	299	185	176	109	278	172	0.2270
04:45	313	194	179	110	289	179	0.2310
05:45	339	210	190	117	352	218	0.2420
10:00	386	239	235	145	669	414	0.2640
10:45	363	224	234	144	739	457	0.2680
12:45	323	200	229	142	744	460	0.2740
13:00	286	177	193	119	764	473	0.2770
19:45	130	80	253	156	642	397	0.2810
20:30	127	79	257	159	615	381	0.2840

Table 5. Comparison CCT Testing and CCT OMIB-EAC

NO	TIME	TESTING CCT (s)	CCT OMIB-EAC (s)	ERROR (%)
1	00:45	0.2303	0.2220	0.0376
2	04:15	0.2221	0.2270	0.0215
3	04:45	0.2272	0.2310	0.0164
4	05:45	0.2404	0.2420	0.0068
5	10:00	0.2689	0.2640	0.0187
6	10:45	0.2769	0.2680	0.0332
7	12:45	0.2657	0.2740	0.0303
8	13:00	0.2736	0.2770	0.0123
9	19:45	0.2822	0.2810	0.0042
10	20:30	0.2776	0.2840	0.0227

In Figure 8 it appears that the estimation value of CCT resulted using BP neural network is very similar with the CCT values calculated using the method OMIB-EAC with a very small difference.



## Conclusion

Transient stability is the most important in the operation of electric power system. From simulation of Java Bali system, we have presented back propagation neural network based approach for online estimation critical clearing time under real operating condition. The simulation results show that bp neural network could be estimated accurately and computational efficiency the critical clearing time with the minimum error 0.0042. The conclusion is the proposed approach is suitable for online critical clearing time estimation.

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