# Transient Stability Analysis of the IEEE 14-Bus Power System Using DCPS

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*Abstract*—**Transient stability is a very important aspect in any electrical network design. Recently, transient stability has become more and more important because of the increasing stress in electrical network. Therefore, transient stability analysis is needed to determine the effectiveness of a particular electrical network and its ability to withstand disturbances while maintaining the quality of service. There are many methods available to perform the transient stability analysis. This paper covers the usage of Dynamic Computation for Power Systems (DCPS) to perform the transient stability analysis of the IEEE 14-bus power system. The bus data, branch data, generator data and exciter data are loaded into DCPS and the transient stability analysis can be carried out. It started with the power-flow solution and end when the waveforms desired are obtained.**

***Keywords: transient stability analysis; DCPS; power-flow solution; critical clearing time***

## I. INTRODUCTION

Nowadays, electrical power system is growing rapidly and is expected to keep growing in the near future due to growing industries and population. However, the growth of electrical power system is not only in terms of its increasing size but also increase in its complexity. Apart from that, equipment nowadays has become more sensitive to disturbances because of the reduction in its size caused by the increasing usage of power electronic devices. The increasing cost of addition and modifications has also made it imperative that utilities consider a range of design options, and perform detailed study of the effect on the system of each option, based on a number of assumptions: normal and abnormal operating conditions, peak and off-peak loadings, and present and future years of operation [1]. Therefore, designing an electrical system nowadays became more complex thus made the role transient stability analysis more crucial.

Transient stability is the ability of a power system to maintain its stability when experiencing severe transient disturbance, such as fault on transmission facilities, sudden loss of generation, or sudden loss of a large load [2]. Transient stability analysis aims to assess the dynamic behaviour of a power system in a fast and accurate way [3]. Many methods have been introduced to perform the transient stability analysis. Methods normally employed to assess transient stability are by using time domain simulation, direct and artificial intelligence methods [4]. Time domain simulation and direct methods are considered most accurate but are time consuming and need heavy computaional effort [4]. Through transient stability analysis, the critical clearing time ($t_{CCT}$) of a power system can be determined. In the evaluation the transient stability of a power system, the critical clearing time plays a very important part. The critical clearing time is defined as the maximum time allowed for the fault to be cleared to maintain the synchronism of the system. The clearing time on the other hand is the time interval between the moment of the disturbance and the moment clearance of the disturbance. The critical clearing time can be determined by increasing the clearing time in time-steps until the system started to experience instability. The greater the $t_{CCT}$, the lower the protection system rating needed as it allows the system to have more time to clear the fault hence reducing its cost and at the same time make the protection system more reliable [5].

The objective of this study is to assess the transient stability of the IEEE 14-bus power system through the waveforms of bus terminal voltage and rotor angle, speed and output power of the machines with respect to clearing time of the fault thus determining the critical clearing time of the system. Section II gives a brief overview on the DCPS software. Section III explains the representation of the dynamic devices involved in the power system through several Differential Algebraic Equations (DAEs). Section IV provides a brief description of transient stability analysis. Section V shows the result of the transient stability analysis. Section VI wraps up the paper.

## II. DYNAMIC COMPUTATION FOR POWER SYSTEMS (DCPS)

The Dynamic Computation for Power Systems (DCPS) program was designed by the former managing director of Advanced Power Solutions Sdn Bhd, the late Dr Sallehhudin Yusof for research purposes [6]. DCPS is designed to be able to perform three types of simulations namely; (i) load flow, (ii) transient stability analysis and (iii) coherency grouping [6]. In this investigation, only the coherency grouping was not used. Before proceeding with the transient stability analysis, it is a requirement that the load flow analysis to be done first to

analyze the steady-state condition of the system. The load flow calculations can be performed using three calculation methods which are: (i) Gauss-Seidel, (ii) Full Newton and (iii) Decoupled Newton. Although all three methods fulfill the objective of performing the load flow calculations, the results obtained from them may differ. In DCPS, the Decoupled Newton method is said to provide the most persist and accurate result. [5].

## III. The Modified Euler Method in the Solution of Differential Algebraic Equations (DAEs)

A power system is made of a number of dynamic devices which when embedded together will add up into a large complex system [5]. Synchronous machine, exciter and turbine-governor are examples of dynamic devices that are considered most important in a power system. The three devices are related to each other and that relationship is represented in Figure 1.

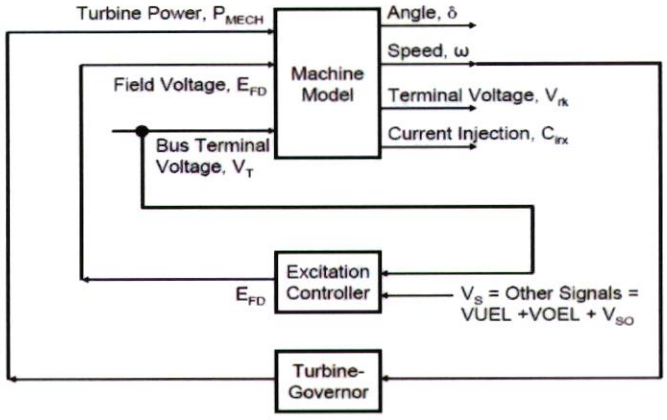



Figure 1. Relationship Between Machine States and Controller Quantities

In transient stability analysis, all three devices are represented by Differential Algebraic Equations (DAEs). The general form first-order DAEs are:

$$dy/dt = f(y,t) \quad (1)$$

where y(t) is a time-varying function with the initial condition of: $y(0) = y_0$. However, the solution of the initial value has to be done numerically since it cannot be solved analytically. Solving (1) results in $y_0, y_1, y_2, \ldots y_i$ at time $t_0, t_1, t_2, \ldots t_i$. The DAEs can be solved by using two classes of methods which are the implicit and explicit numerical integration techniques [5]. The Trapezoidal method is considered the most common method under the implicit technique while the Runge-Kutta and the Euler's method are the two most common method under the explicit technique. In DCPS, the Modified Euler Method, otherwise known as the Predictor-Corrector Method, was used to represent the explicit numerical integration technique. Predictor Formula to calculate the initial estimate value is as following [5]:

$$y_{i+1}^{P} = y_i + hf(y_i, t_i) \quad (2)$$

The time-step, h is given by ($\Delta t = t_{i+1} - t_i$). In this paper, the value used for $\Delta t$ is 0.005s. By applying the following Corrector Formula using the result in (2), the final estimate value can be calculated [6]:

$$y_{i+1}^{C} = y_i + 0.5h[f(y_i, t_i) + f(y_{i+1}^{P}, t_{i+1})] \quad (3)$$

The Modified Euler method can be represented graphically in Figure 2.

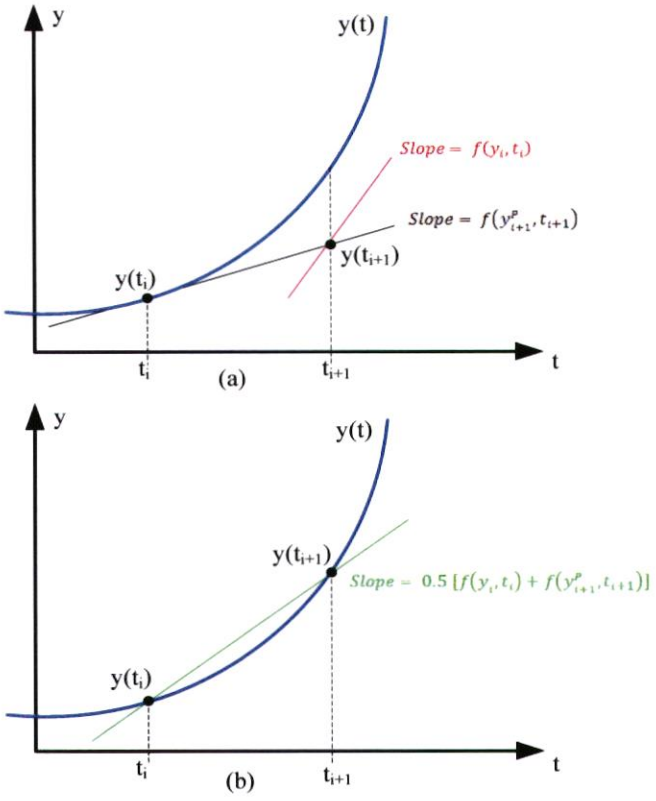



Figure 2. Graphical Representation of Modified Euler Method: (a) Predictor and (b) Corrector

### A. Synchronous Machine Model

In DCPS, the synchronous machine are represented by one of three models to be used for the transient stability analysis. The three models mentioned are the: (i) classical machine model, (ii) transient level model and (iii) generator detailed model. In this paper, all the generators in the system are represented by the transient level model while all synchronous compensators are represented by the classical machine model. The equations involved in representing the transient level model are [7]:

$$d\delta_i/dt = \omega_i - 2\pi f \quad (4)$$

$$d\omega_i/dt = ((P_m - P_e - (\omega_i - 2\pi f)D_i)/M_i \quad (5)$$

$$dE'_{qi}/dt = (E_{fdi} - E'_{qi} + (x_{di} - x'_{di})I_{di})/T'_{do} \quad (6)$$

$$dE'_{di}/dt = (-E'_{di} - (x_{qi} - x'_{qi})I_{qi})/T'_{qo} \quad (7)$$

Where $\delta_i$ is the rotor angle; $\omega_i$ is the angular velocity; $P_m$ is the input mechanical power; $P_e$ is the output electrical power; $D_i$ is the damping factor per unit; $M_i$ is the inertia constant in MW-s on machine base MVA; f is the system frequency; $x_{di}$ is the direct-axis synchronous reactance in per unit on machine base MVA; $x'_{di}$ is the direct-axis transient reactance in per unit on machine base MVA; $T'_{do}$ is the open circuit direct-axis transient time constant in seconds; $x_{qi}$ is the quadrature-axis synchronous reactance in per unit on machine base MVA; $x'_{qi}$ is the quadrature-axis transient reactance in per unit on machine base MVA and $T'_{qo}$ is the open circuit quadrature-axis transient time constant in seconds. The equations involved in representing the classical model are [7]:

$$d\delta_i/dt = \omega_i - 2\pi f \quad (8)$$

$$d\omega_i/dt = ((P_m - P_e - (\omega_i - 2\pi f)D_i)/M_i \quad (9)$$

Where all parameters carry the same meaning as the transient level model.

### B. Exciter Model

Besides the synchronous machine, the exciter also plays a very important role in the synchronous generator control system as it controls the magnetic field in the generator system and controls the output voltage. In power system application, the exciter is important to maintain the terminal voltage a certain constant level. There are two types of exciter model to be used in DCPS which are: (i) excitation system with a simple gain and (ii) IEEE type 1 excitation control. The exciter model used in this paper is the excitation system with a simple gain which is shown in Figure 3. The equation involved in this exciter model is [7]:

$$dV_C/dt = (V_T - V_C)/T_R \quad (10)$$

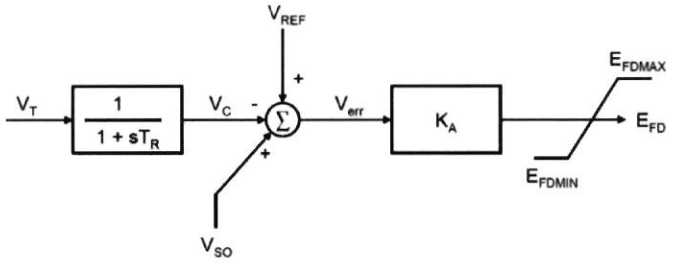



Figure 3. The Excitation System with a Simple Gain

### C. Turbine-Governor Model

The turbine-governor system is very important in power system application. It is a closed loop system that monitors the speed of the rotor, compares it with the synchronous speed and provide appropriate signal to the fuel valve controllers hence controlling the rotor speed. Both rotor speed and synchronous speed must be equal for an electric system to be stable. In DCPS, there are two types of turbine-governor model which are: (i) simple turbine-governor and (ii) PSS/E TGOV1 model with deadband added. The simple turbine-governor model was used in this paper. The block diagram of the model is shown in Figure 4. The equation that represents the simple turbine-governor model is:

$$dP_m/dt = (\omega_{err} - P_m)/T_1 \quad (11)$$

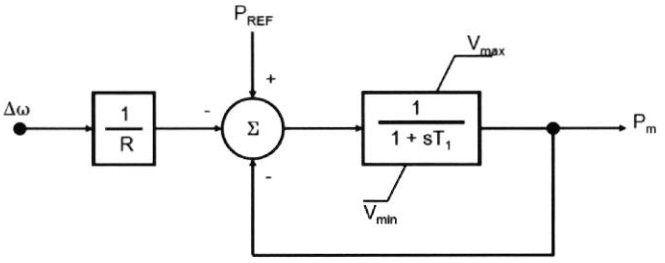



Figure 4. The Simple Turbine-Governor

## IV. Transient Stability Analysis Using DCPS

### A. Load Flow Analysis

Load flow analysis is an analysis of voltages, currents, and power flows in a power system under steady-state conditions [8]. Using DCPS, to perform transient stability analysis, it is a must that the load flow analysis is done first to give the steady-state parameters to be used in calculating the initial condition of the dynamic components. The DCPS load flow program reads the bus and branch data prepared beforehand and solves the load flow through a series of steps. In this paper, the lengthy calculation in load flow analysis is done using the Decoupled Newton Method. The Decoupled Newton Method calculates the steady-state parameters through a series of iterations. To ensure the load flow solution satisfies for the transient stability analysis, the real and reactive power mismatch are ensured to be very close to zero which means the load flow is solved and no more iterations are needed.

### B. Transient Stability Analysis

After solving the load flow analysis, the transient stability analysis can be performed. To start the transient stability analysis, the solved load flow solution will be read. Then, the dynamic data will also be read and the calculation to plot the waveform continues. The simulation was run without any disturbance from $t = 0s$ to $t = 1s$. The reason that the simulation was run without disturbance in this time interval is to set a reference value which is the s condition of the system before fault occurs. A three-phase fault was then introduced to the system at $t = 1s$ and removed at the clearing time. In real practice, faults are cleared by the isolation of the infected area from the rest of the system through the opening of circuit breakers [5]. A transiently stable system would be able to recover its original steady-state condition before the fault was injected. To determine the critical clearing time, the clearing time was increased gradually at 0.1s time step. The critical clearing time is the mid-point between the clearing time when the system first started to become unstable and the clearing time when the system is last known to be stable. The steps of performing the transient stability analysis using DCPS can be simplified in a flowchart in Figure 5. The calculation of the critical clearing time is shown graphically in Figure 6.

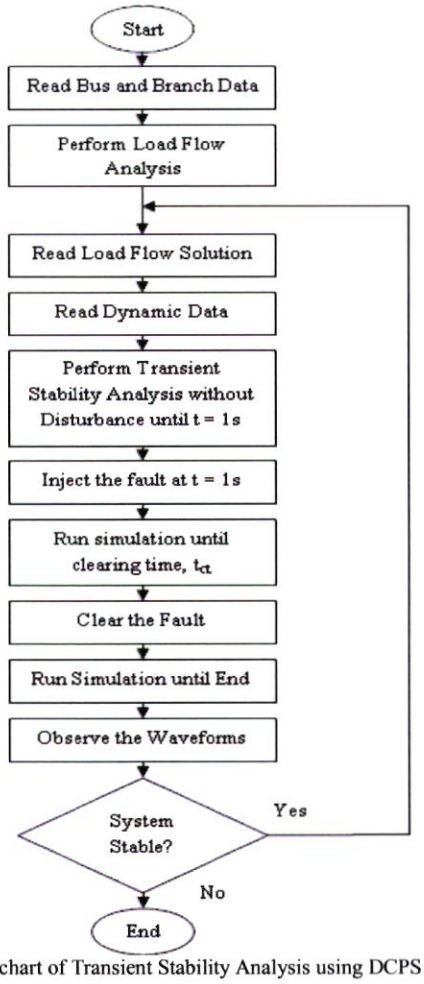



Figure 5. Flowchart of Transient Stability Analysis using DCPS

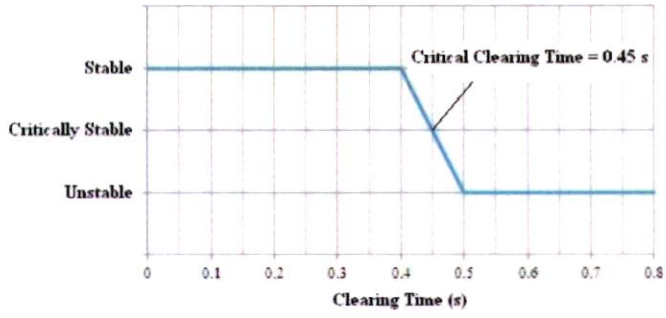



Figure 6. Calculation of Critical Clearing Time

## V. RESULTS AND DISCUSSION

The transient stability analysis has been performed on IEEE 14-bus electric power system through the process mention in section IV. The IEEE 14-bus power system network is shown in Figure 7. The bus data and branch data used in this simulation is a shown in the Appendix. In this IEEE 14-bus system, bus 1 acts as the slack bus. The fault was injected to every bus in the system but only at one bus during each simulation. By applying the fault on each bus, the relationship between the critical clearing time and the distance between the fault location and the slack bus can be determined. The distance between the fault location and the slack bus is measured by the minimum reactance between the two buses.

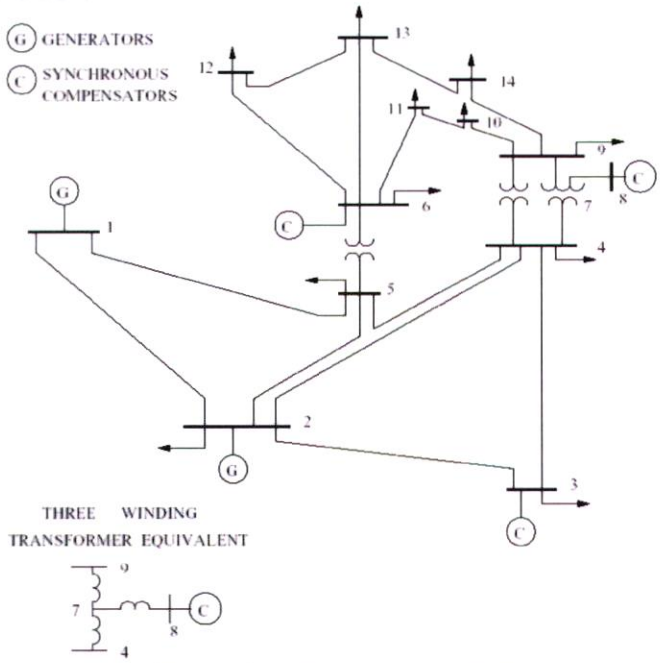



Figure 7. The IEEE 14-Bus Power System

The bus terminal voltage, machine rotor angle, machine speed and machine electrical output power waveforms during fault at bus 1 with clearing time 0.4s is shown in Figure 8, Figure 9, Figure 10 and Figure 11 respectively. The system in this condition is considered as transiently stable since the bus terminal voltages, the machine rotor angles and the machine electrical output power are able to regain synchronism and settle back to their original steady state condition after the fault is injected and cleared. Although the machine rotor angles did return to their original level after the fault is injected and cleared, they are still able to settle to a constant value. Therefore, the system is still considered transiently stable.

When the fault at bus 1 is cleared with the clearing time of 0.5s, the bus terminal voltage, machine rotor angle, machine speed and machine electrical output power waveforms are as in Figure 12, Figure 13, Figure 14 and Figure 15 respectively. This system is considered as transiently unstable since all parameters mentioned above are not able to regain synchronism after the fault is injected and cleared. They are not able to return to their original steady-state condition as before the fault and not even able to settle to a constant value.

From the analysis above, the critical clearing time is determined to be 0.45s based on the method discussed in section IV. From the critical clearing time, we can be sure that if a fault occurred at bus 1 and is cleared in less than 0.45s, the system will be able remain stable. The fault is then injected to other buses and the results are as tabulated in Table 1 sorted from the bus nearest to the slack bus through to the furthest. As proven in the table, the critical clearing time of the system increased as the fault location is further away from the slack bus.

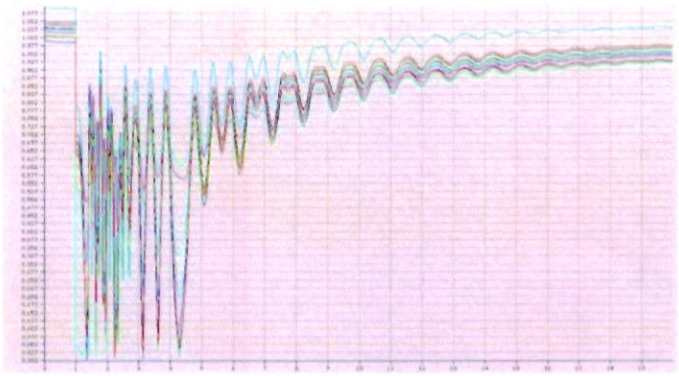


Figure 8. The Bus Terminal Voltage Waveforms ($t_{ct}$ = 0.4s)

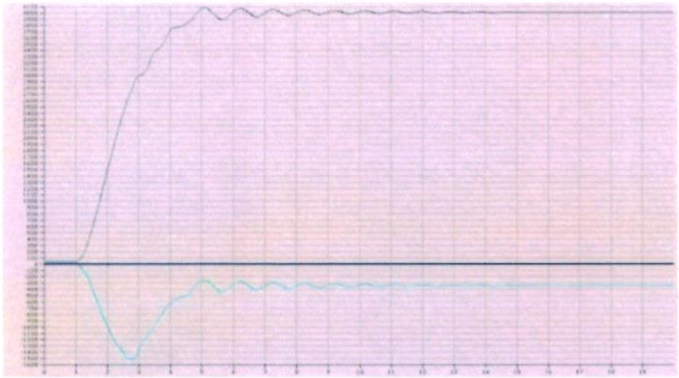


Figure 9. The Machine Rotor Angle Waveforms ($t_{ct}$ = 0.4s)

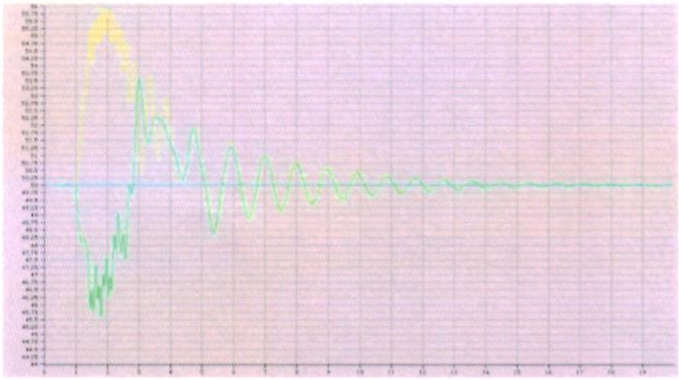


Figure 10. The Machine Speed Waveforms ($t_{ct}$ = 0.4s)

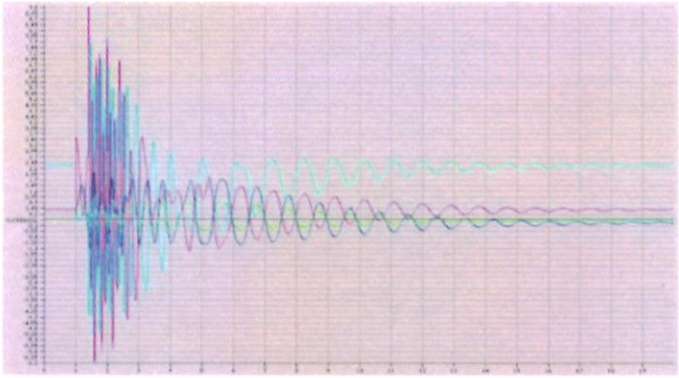


Figure 11. The Machine Electric Output Power Waveforms ($t_{ct}$ = 0.4s)

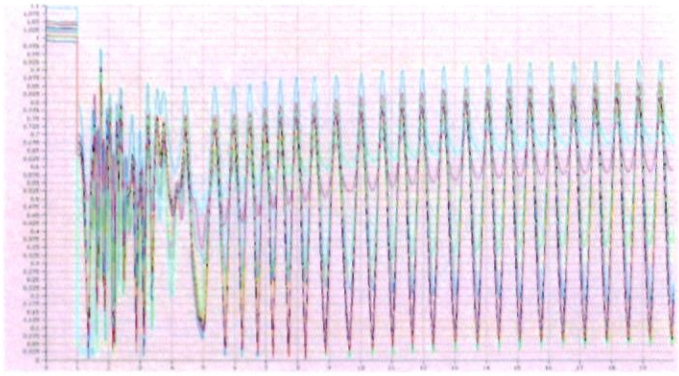


Figure 12. The Bus Terminal Voltage Waveforms ($t_{ct}$ = 0.5s)

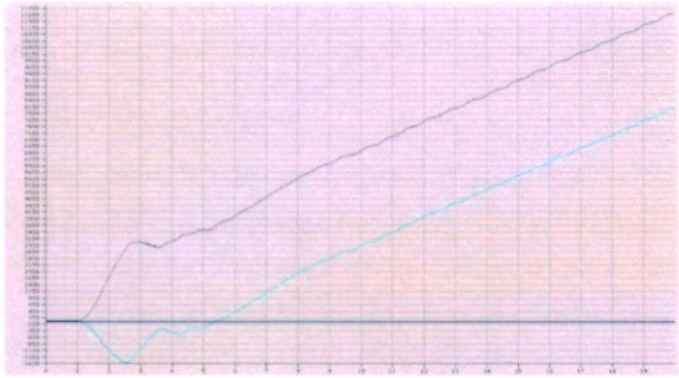


Figure 13. The Machine Rotor Angle Waveforms ($t_{ct}$ = 0.5s)

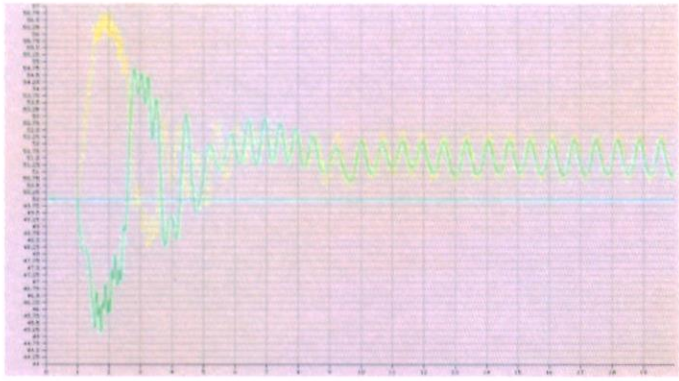


Figure 14. The Machine Speed Waveforms ($t_{ct}$ = 0.5s)

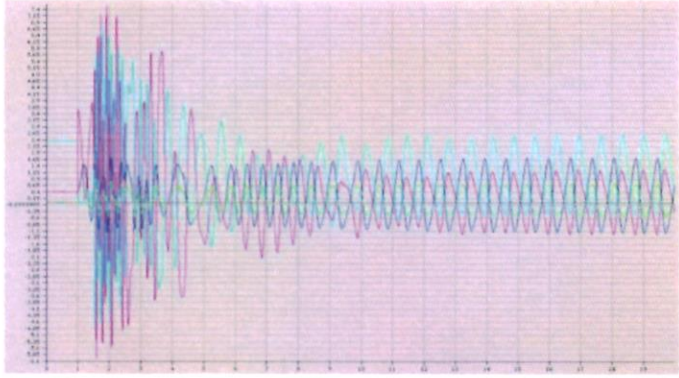


Figure 15. The Machine Electric Output Power Waveforms ($t_{ct}$ = 0.5s)

TABLE 1. THE CRITICAL CLEARING TIME OF THE SYSTEM FOR FAULT AT EACH BUS

| Faulted Bus | Minimum Reactance to Slack Bus (p.u.) | Critical Clearing Time (s) |
|---|---|---|
| 1 | 0.00000 | 0.45 |
| 2 | 0.05917 | 2.55 |
| 4 | 0.23549 | 5.05 |
| 3 | 0.25714 | 6.45 |
| 7 | 0.44461 | 8.75 |
| 6 | 0.47506 | 10.85 |
| 9 | 0.55462 | 11.65 |
| 13 | 0.60533 | ∞ |
| 8 | 0.62076 | 38.75 |
| 10 | 0.63912 | 32.75 |
| 11 | 0.67396 | ∞ |
| 12 | 0.73087 | ∞ |
| 14 | 0.82500 | ∞ |

## VI. CONCLUSION

The transient stability of the IEEE 14-bus power system has been assessed using DCPS. Fault in an electric power system needs to be cleared within the critical clearing time for the system to regain its synchronism and maintain its stability. The Figure 8-15 shows the comparison between the waveforms of a transiently stable system and transiently unstable system caused by fault clearance quicker and later than the critical clearing time respectively. The critical clearing time of the system also increased as the fault location is further from the slack bus. In other words, the fault becomes less severe as it moves further away from the slack bus which gives it more time to be cleared.

## ACKNOWLEDGMENT

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## APPENDIX

TABLE 2. BUS DATA USED IN DCPS

| Bus No. | Bus Type* | $V_T$ (p.u.) | $P_G$ (p.u.) | $P_L$ (p.u.) | $Q_L$ (p.u.) | $V_{BASE}$ (kV) |
|---|---|---|---|---|---|---|
| 1 | 3 | 1.060 | 2.32 | 0.0000 | 0.0000 | 69.0 |
| 2 | 2 | 1.045 | 0.40 | 0.2170 | 0.1270 | 69.0 |
| 3 | 2 | 1.010 | 0.00 | 0.9420 | 0.1900 | 69.0 |
| 4 | 0 | 1.019 | 0.00 | 0.4780 | -0.0390 | 69.0 |
| 5 | 0 | 1.020 | 0.00 | 0.0760 | 0.0160 | 69.0 |
| 6 | 2 | 1.070 | 0.00 | 0.1120 | 0.0750 | 13.8 |
| 7 | 0 | 1.062 | 0.00 | 0.0000 | 0.0000 | 13.8 |
| 8 | 2 | 1.090 | 0.00 | 0.0000 | 0.0000 | 18.0 |
| 9 | 0 | 1.056 | 0.00 | 0.2950 | 0.1660 | 13.8 |
| 10 | 0 | 1.051 | 0.00 | 0.0900 | 0.0580 | 13.8 |
| 11 | 0 | 1.057 | 0.00 | 0.0350 | 0.0180 | 13.8 |
| 12 | 0 | 1.055 | 0.00 | 0.0610 | 0.0160 | 13.8 |
| 13 | 0 | 1.050 | 0.00 | 0.1350 | 0.0580 | 13.8 |
| 14 | 0 | 1.036 | 0.00 | 0.1490 | 0.0500 | 13.8 |

*Bus Type: 3 = slack bus, 2 = generator bus, 0 = load bus

TABLE 3. BRANCH DATA USED IN DCPS

| From Bus | To Bus | R (p.u.) | X (p.u.) | B (p.u.) | Tap Ratio |
|---|---|---|---|---|---|
| 1 | 2 | 0.01938 | 0.05917 | 0.0528 | 0.000 |
| 1 | 5 | 0.05403 | 0.22304 | 0.0492 | 0.000 |
| 2 | 3 | 0.04699 | 0.19797 | 0.0438 | 0.000 |
| 2 | 4 | 0.05811 | 0.17632 | 0.0374 | 0.000 |
| 2 | 5 | 0.05695 | 0.17388 | 0.0340 | 0.000 |
| 3 | 4 | 0.06701 | 0.17103 | 0.0346 | 0.000 |
| 4 | 5 | 0.01335 | 0.04211 | 0.0128 | 0.000 |
| 4 | 7 | 0.00000 | 0.20912 | 0.0000 | 0.978 |
| 4 | 9 | 0.00000 | 0.55618 | 0.0000 | 0.969 |
| 5 | 6 | 0.00000 | 0.25202 | 0.0000 | 0.932 |
| 6 | 11 | 0.09498 | 0.19890 | 0.0000 | 0.000 |
| 6 | 12 | 0.12291 | 0.25581 | 0.0000 | 0.000 |
| 6 | 13 | 0.06615 | 0.13027 | 0.0000 | 0.000 |
| 7 | 8 | 0.00000 | 0.17615 | 0.0000 | 1.000 |
| 7 | 9 | 0.00000 | 0.11001 | 0.0000 | 1.000 |
| 9 | 10 | 0.03181 | 0.08450 | 0.0000 | 0.000 |
| 9 | 14 | 0.12711 | 0.27038 | 0.0000 | 0.000 |
| 10 | 11 | 0.08205 | 0.19207 | 0.0000 | 0.000 |
| 12 | 13 | 0.22092 | 0.19988 | 0.0000 | 0.000 |
| 13 | 14 | 0.17093 | 0.34802 | 0.0000 | 0.000 |