International Journal of Electrical and Computer Engineering (IJECE)
Vol. 13, No. 1, February 2023, pp. 125~133
ISSN: 2088-8708, DOI: 10.11591/ijece.v13i1.pp125-133

Critical clearing time estimation of multi-machine power system transient stability using fuzzy logic

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Article Info

Article history:

Received Dec 14, 2021
Revised Aug 8, 2022
Accepted Aug 19, 2022

Keywords:

Artificial intelligence
Critical clearing time
Fuzzy logic
Power system transient stability
Time-domain simulation

ABSTRACT

Studying network stability requires determining the best critical clearing time (CCT) for the network after the fault has occurred. CCT is an essential issue for transient stability assessment (TSA) in the operation, security, and maintenance of an electrical power system. This paper proposes an algorithm to obtain CCT based on fuzzy logic (FL) under fault conditions, for a multi-machine power system. CCT was estimated using a two-step fuzzy logic algorithm: the first step is to calculate Δt, which represents the output of the FL, while maximum angle deviation (δmax) represents the input. The second step is to classify the system if it is a stable or unstable system, based on two inputs for FL, the first mechanical input power (Pm), the second average accelerations (Aav). The results of the proposed method were compared with the time domain simulation (TDS) method. The results showed the accuracy and speed of the estimation using the FL method, with an error rate not exceeding 5%, and reduced the performance time by about half the time. The proposed approach is tested on both IEEE-9 bus and IEEE-39 bus systems using simulation in MATLAB.

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1. INTRODUCTION

The interest in controlling the transient situations that the electric power systems are exposed to has become an important issue that the generation, transmission and distribution of electric power companies seek. Interest in these aspects has increased over time, and methods and techniques have been continuously developed to keep pace with the complexities and breadth of electrical power systems [1], [2]. The study of stability and its analysis is very important to know the possibility of maintaining the stability of the system when disturbances occur, such as transmission line malfunctions, sudden change of electrical loads, sudden loss of units, as well as known malfunctions, which are cases of short circuits that the electrical system may be exposed to. Which may cause, in the event of the fault being large, to lose the synchronization state of a generator with the rest of the generators in the system, which leads to a state of imbalance or stability in the system, and these disturbances may affect frequency and voltage [3], [4].

Critical clearing time (CCT) is the maximum time during which a fault must be cleared to maintain system stability. The CCT is measured and compared with the fault clearing time (FCT) in direct stability estimation methods. The transient system is known to be stable if the CCT is greater than the FCT [5]–[7].

The importance of CCT estimation is due to the development and expansion of the operational range of generators. Usually, the relays are tuned to trip a signal by calculating the CCT obtained from conventional methods and for different operating conditions. However, the relay may issue a wrong decision if there is a change in these operating conditions. Accordingly, the researchers tended to use artificial intelligence for calculating CCT and in different operating conditions [8], [9].

Several techniques have been used to assess transient stability, including the traditional time-domain method, numerical integration, probabilistic methods based on the Labenov technique, recently artificial intelligence techniques. The effect of adding flexible alternating current transmission systems (FACTS) to enhance the transient stability of the system and increase the critical clearing time after a major fault or sudden change in load levels has been studied by studied by Azeez and Abdelfattah [10]. Priyadi *et al.* [11] suggested the control of unstable equilibrium point (CUEP) method to obtain CCT, and through this method, the critical power of each generator in the system is determined with an allowable error of 0.01% and the control of the unstable equilibrium point at any fault. The researchers proved that this method is more accurate to Determine stability through numerical operations. Abdelaziz [12] used fuzzy logic technique to classify the system, whether it is stable or not, and the results revealed that the proposed system is flexible and extendable. Nair *et al.* [13] consider the range for which the value of the CCT changes with the change of the fault location, the increase of the load systematically and the change of the value of the fault resistance. Variation of CCT is observed using eigen value analysis method in MATLAB/PSAT platform. Sulistiawati *et al.* [14] used two methods to calculate CCT, the first is numerical, which is the critical path method based on critical generation, and the second method the CCT is learned by extreme learning machine (ELM) and this method has the ability to calculate CCT with changing loads and for various faults, they showed that these methods give CCT is accurate with error rate 0.33% for the neural networks (NN) method an average error of 0.06% for the (ELM) method. After studying the transient stability of the oscillation equation and the equal area criterion, the researcher Lin [15] clarified that there is a relationship between power factor and frequency with CCT, and this relationship is direct with power factor and inverse with frequency. Sharma *et al.* [16] derive an equation or formula linking CCT with the system parameter, where this formula gives an insight into the effect of system components on transient stability such as system impedance and generator moment of inertia. The study was conducted on a system 39 bus. Fuzzy logic (FL) used to estimate CCT in a multi-machine both IEEE-9bus and IEEE-39 bus systems. These systems are modeled in MATLAB 2017/Simulink.

2. SIGNIFICANCE OF THE RESEARCH

CCT main the maximum allowable time for which the system remains stable after the occurrence of the fault in the power system, evaluating the CCT is very important to maintain stability and not prone to collapse after the fault. There are several methods used to calculate CCT, such as time domain simulation (TDS), and numerical analysis of nonlinear differential equations. These methods give accurate results for a long time as a result of the many iteration processes. This is so inefficient when utilized for transient stability analysis. Because the disturbances occur very quickly in the system. Therefore, we need methods that can reduce the required computing time to calculate CCT such as artificial intelligence methods. In this research, fuzzy logic was used to reduce the computation time to calculate CCT. The results proved a high degree of accuracy and speed of evaluation.

3. FUZZY LOGIC

FL is a way of dealing with undefined and uncertain data for problems that have more than one solution. Logic is two types: binary logic and fuzzy logic. It was used by the scientist Lutfi Zadeh at the University of California for the first time in 1965, as it was found that FL is multi-valued logic, as it builds intermediate values between traditional values such as true/false and high/low. Fuzzy systems are an alternative to traditional ideas they can be represented by organic and logical groups that have their origins in ancient Greek philosophy the structure of the FL system is shown in Figure 1 [17], [18].

3.1. Fuzzification

It is the first part in the structure of FL in which the process of converting the regular (Crisp) value entries into fuzzy variables of different degrees of belonging to the fuzzy groups. And these are ready for processing in the fuzzy deduction machine. The fuzzy consists of a set of functions belonging to the fuzzy groups including their shapes, number, maximum values, and the number of interventions between them in determining the linguistic values of the fuzzy variables [19].

3.2. Rules base

It is a set of fuzzy laws that relate fuzzy inputs to outputs. There can be multiple entries with one output. Setting rules is the vital and most important part when designing fuzzy logic, which is a set of logical semantic rules in the form: If…..And….Then [19].

3.3. Inference engine

It represents the basis of the structure of FL, as it has the ability to represent human decision making based on fundamentals of FL, using two main methods of inference. The first is the Min-Max method. The second is fuzzy additive to be able to deduce FL actions using fuzzy implication and inference rules in FL, i.e. the process of deduction is carried out based on the values of the inputs for fuzzy sets [20].

3.4. Defuzzification

Reverse fuzzy this is the last stage in the structure of FL. It is the opposite process of fuzzy, i.e. converting fuzzy functions to regular functions (Crisp). There are several de-fuzzing methods that determine the final output value as the centroid or center of gravity technique to find the equilibrium point of the solution [21].

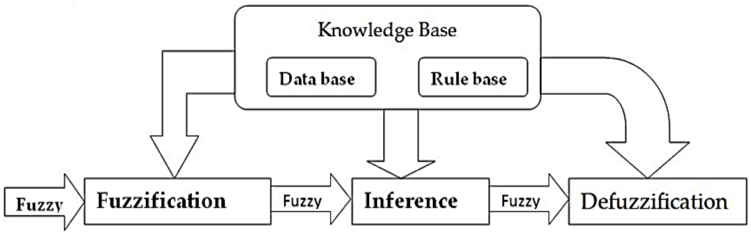

Figure 1. Structure of the FL system [22]

4. PROPOSED METHOD FOR OBTAINING CCT

4.1. TDS method [23]

The value of CCT is estimated from the simulation by increasing the value of the fault clearance time until the system reaches an unstable state, as follows:

Step 1: Set an initial value for FCT=t_o.

Step 2: Impose initial time limits by decreasing the value of t_o by α t_o get the lower bound $t_1=t_o-\alpha$ and increasing the value of t_o by α to get the upper bound $t_2=t_o+\alpha$.

Step 3: The system is checked if it is stable or unstable. If it is stable, the lower bound value is replaced by $t_1=t_1+\alpha$ and the upper bound value is replaced with the value $t_2=t_2+\alpha$. Then the system stability is checked at the new values and we continue to change the value of the lower and upper bound until we get that at one of these two values the system is stable and at the other value, the system is unstable. Move to the step 4.

Step 4: The middle value between the upper and lower bounds is tested. If the system is stable, the lower bound value is replaced with the median value. If the system is unstable, the upper bound value is replaced by the median value to perform the time calculation again.

Step 5: This process continues until we reach the value of the acceptable tolerance between the limits, then the value of CCT is determined t_o be the upper limit t_2.

4.2. Fuzzy logic method

Figure 2 represent the flowchart of the proposed algorithm to estimate the CCT using FL. The value of the CCT is estimated using two-step FL: the first step is to calculate Δt, which represents the output of the FL, while maximum angle deviation (δmax) represents the input of the FL with triangular membership functions for its mathematical simplicity for representation of eight of linguistic variable (δmax) with eight of the linguistic variables for output as shown Figure 3. For the input δmax and output Δt, the proposed fuzzy system is divided as subsets as follows: vs (very small), ms (medium small), ls (large small), sl (small large), mL (medium large), vl (very large), ll (large large), ll1 (large large1), ss (small small).

The second step is to classify the system if it is a stable or unstable system, based on two inputs for FL, the first input is the mechanical input power (Pm), and as it is known, the higher the load of the system, the greater the chance of the system going into an unstable state. 'Pm' get from load flow results. The second input is the average acceleration (Aav) during the fault, which represents the mean value of the two rotor angular accelerations A1 at the moment of fault, and A2 at the moment of clearing the fault. The two features are specified from a transient stability study for a machine. The two previous variables, which are the inputs of the proposed FL system, to classify the system if it is stable or unstable are divided as subsets as:

- Pm: L (light), N (normal), H (high)
- Aav: VS (very small), S (small), M (medium), L (large), VL (very large)

Figure 4 show the membership functions for inputs Pm and Ava and output.

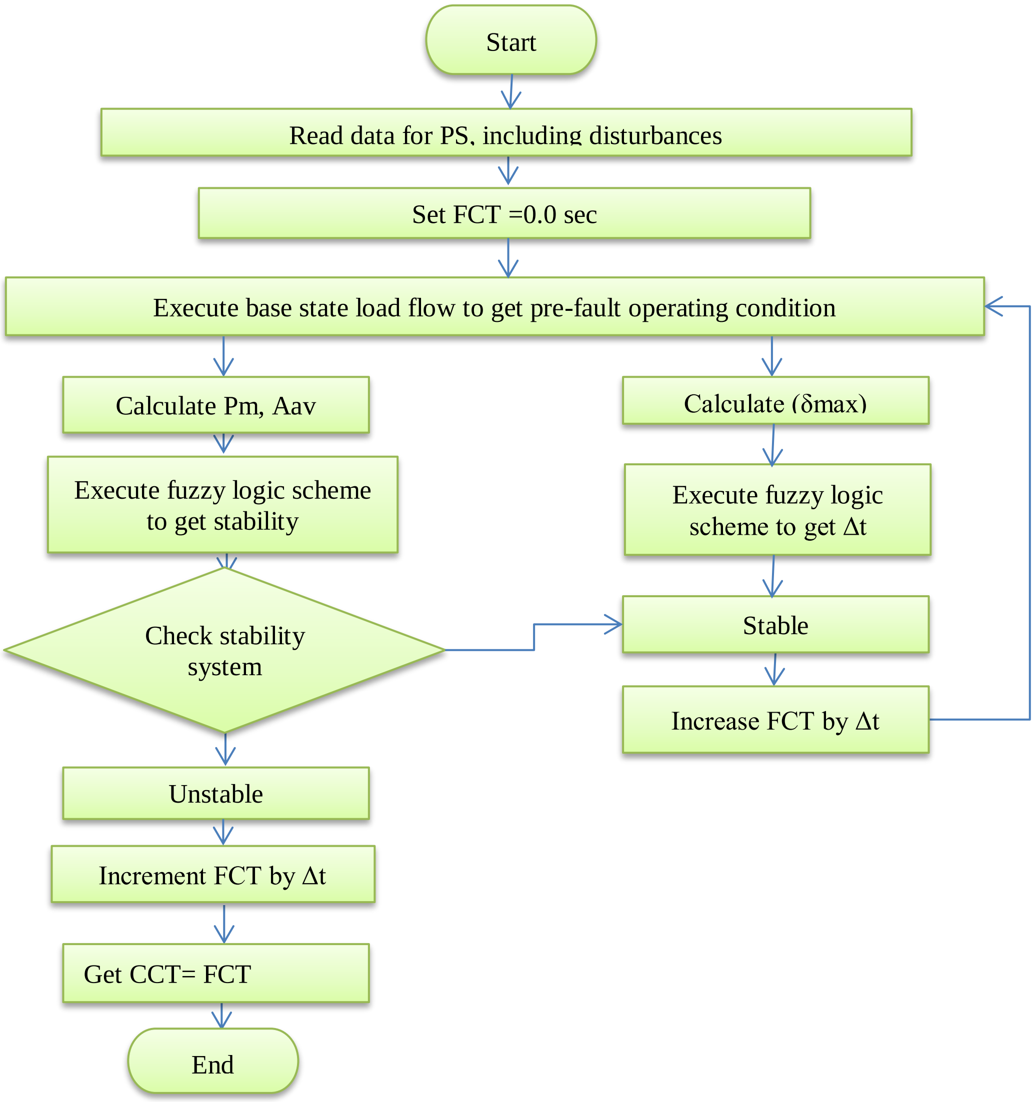

Figure 2. Flowchart of the proposed algorithm to estimate the CCT using FL

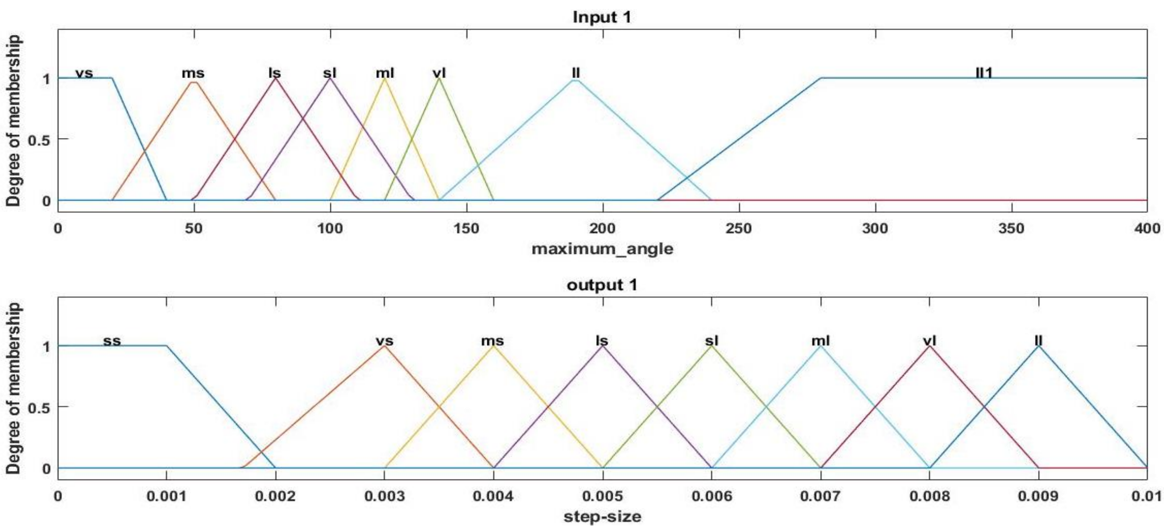

Figure 3. Eight Triangular membership functions for input δmax in degree and output Δt

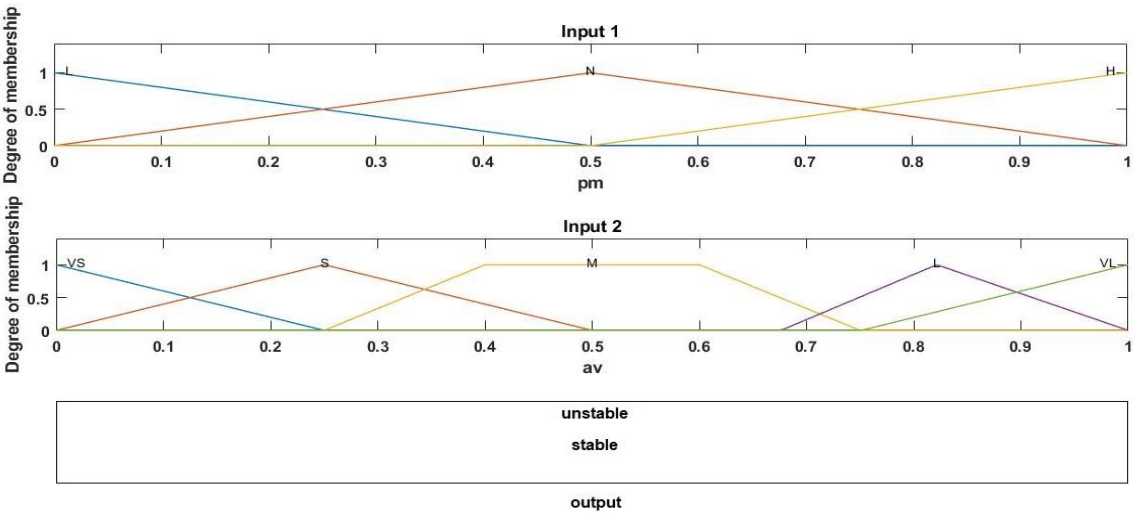

Figure 4. Membership functions for inputs Pm, Aav and output

5. RESULTS AND DISCUSSION

The fuzzy logic system (FLS) method and TDS method are carried out to estimate the CCT using the IEEE 9-Bus system and NE 39-Bus system as shown in Figures 5 and 6, respectively and the information of these systems are appearing in [24], [25]. Simulation is carried out by applying a three-phase fault to an evaluation of the performance of the proposed method. Figure 7 shows the voltage signals with time after three phase fault occurs between bus 8 and bus 9 in the IEEE 9-Bus system at a time equal to 0.5 sec. It is obvious that the voltage values decrease after the fault with different values depending on the location of the buses from the location of the fault. However, these values return to stability at values very near the nominal values at FCT is 0.714 sec. Increasing the value of FCT to 0.715 sec causes the system to lose its stability as shown in Figure 8. The same fault was applied to the NE 39-Bus system between bus 25 and bus 26. Figures 9 and 10 show the signal voltages with time for all buses when the FCT is equal to 0.71 and 0.72 sec respectively. We notice from Figure 9 that the system maintained its stability while it lost its stability in Figure 10.

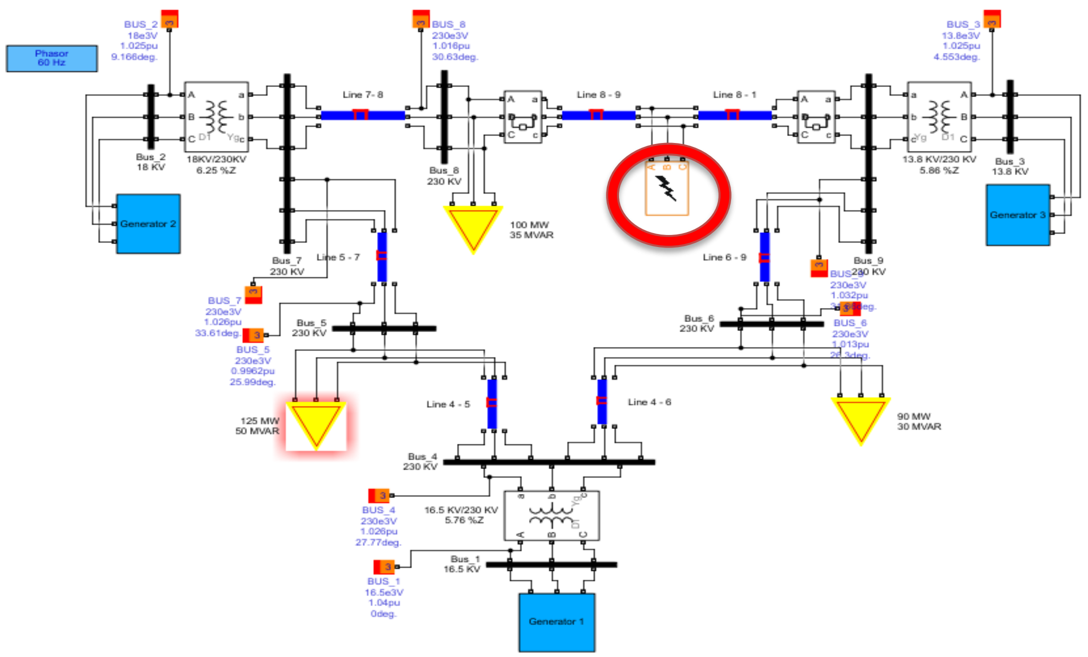

Figure 5. IEEE 9-Bus system is used as the test system, which is simulated in MATLAB

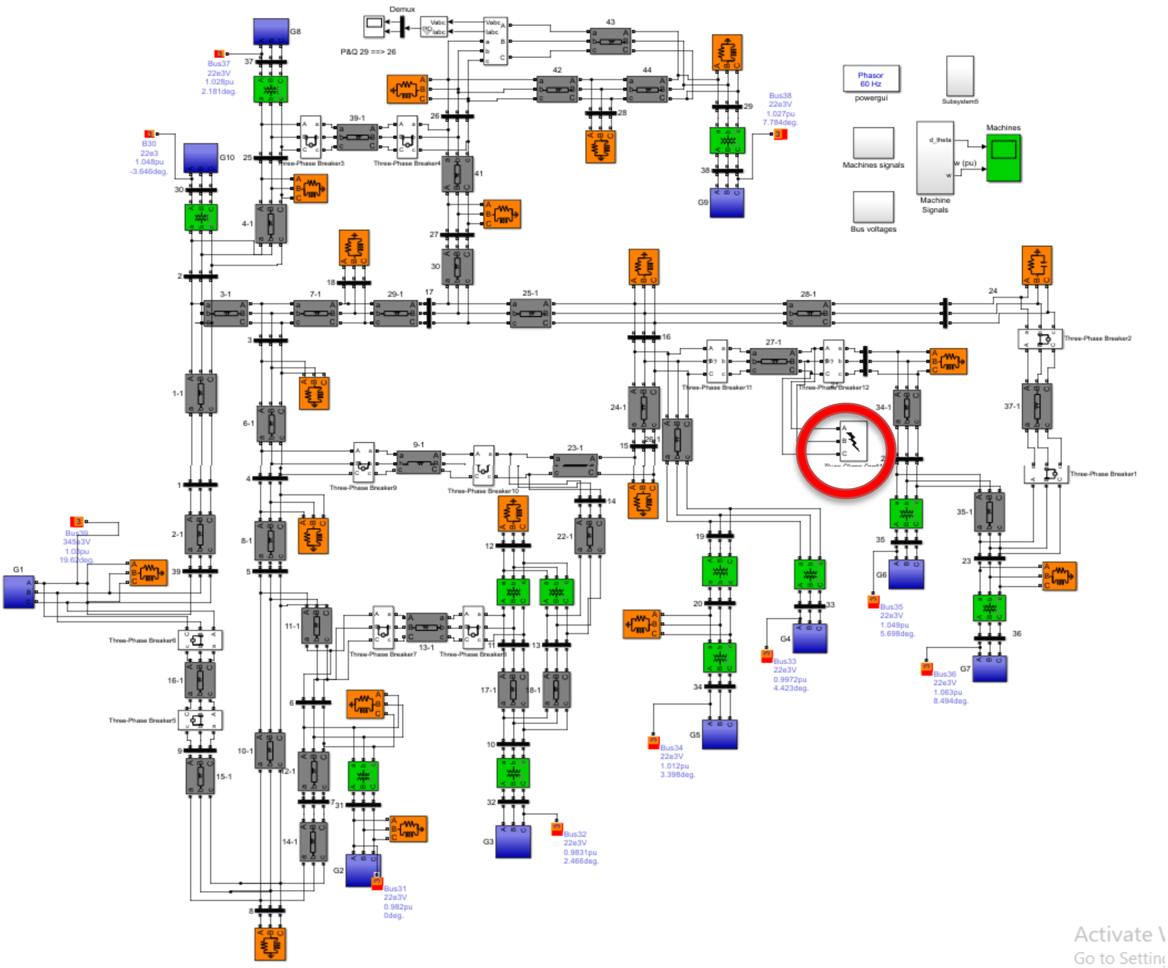

Figure 6. NE 39-Bus system is used as the test system, which is simulated in MATLAB

Table 1 shows the results of the estimation of CCT values and performance time obtained from the TDS method and the proposed FLS method for IEEE 9-Bus after applying a three-phase fault in different locations and Table 2 shows the same results for NE 39-Bus system. Tables 1 and 2 shows the estimated values of CCT and the performance time for each of the FL method and the TDS method. From the tables, we note that the error for all cases is a small percentage, and this proves the accuracy of estimating values of CCT in the FL method compared with the TDS method, in addition to reducing the time of performance by FL method to half of the time of performance using the TDS method. tables pointed that the fault is near that certain bus and the Fault bus number is The line that was taken out of the system

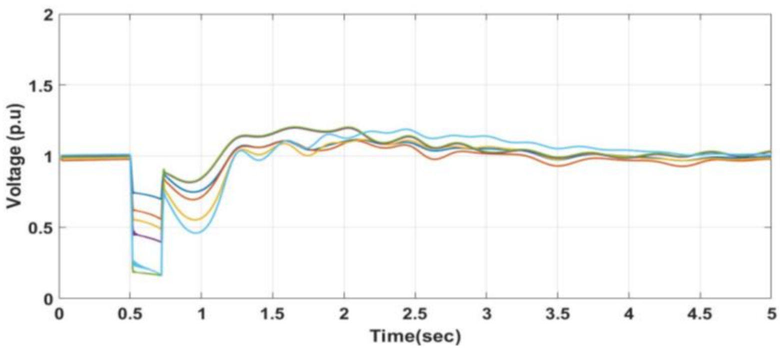

Figure 7. The voltage buses for FCT=0.714 sec

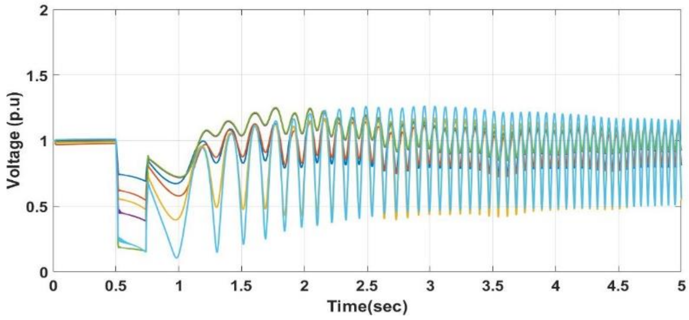

Figure 8. The voltage buses for FCT=0.715 sec

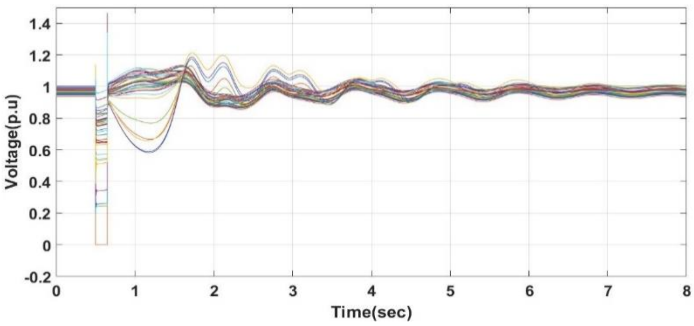

Figure 9. The voltage buses for FCT=0.71 sec

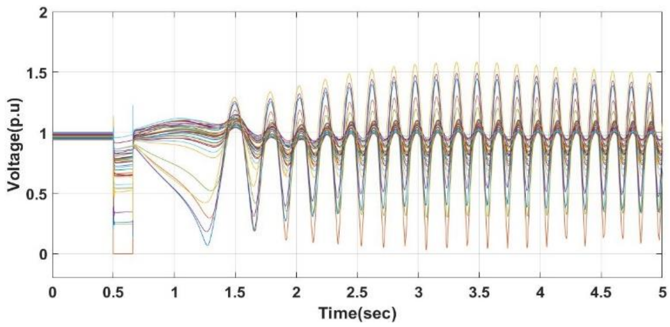

Figure 10. The voltage buses for FCT=0.72 sec

Table 1. CCT and performance time for IEEE 9-Bus

Fault bus Number	CCT using TDS (s)	CCT using FLS (s)	Error (100%)	Performance Time using TDS (m)	Performance Time using FLS (m)	Error (100%)
Bus 9 -Bus 6	0.665	0.642	3.58	20.35	9.44	0.463
Bus 7 -Bus 5	0.631	0.603	4.64	21.56	10.21	0.473
Bus 8 -Bus 9	0.714	0.712	0.281	19.56	10.34	0.528
Bus 7 -Bus 8	0.697	0.702	-0.712	18.87	9.67	0.514
Close to Bus 9	0.639	0.609	4.92	22.21	10.91	0.491
Close to Bus 6	0.713	0.698	2.14	19.11	9.32	0.487

Table 2. CCT and performance time for NE 39-Bus

Fault bus Number	CCT using TDS (s)	CCT using FLS (s)	Error (100%)	Performance Time using TDS (m)	Performance Time using FLS (m)	Error (100%)
Bus25-bus26	0.71	0.702	1.14	18.98	10.98	0.578
Bus23-bus24	0.702	0.689	1.88	19.66	9.89	0.503
Bus9-bus39	0.8	0.772	3.63	20.91	12.11	0.578
Bus6-bus11	0.77	0.81	4.93	21.45	9.91	0.462
Bus4-bus14	0.76	0.779	-2.44	18.32	11.21	0.611
Bus21-bus22	0.65	0.684	-4.97	18.47	10.99	0.595

6. CONCLUSION

An accuracy and fast calculation methodology for the estimation of CCT is suggested in this paper, by using two simulation systems IEEE 9-bus and NE 39-Bus to test the capabilities of the proposed algorithm. The simulation results show the efficiency of the FL method, after calculating the CCT for both methods and calculating the % error, which does not exceed 5%. The FL method is also used to reduce the performance time compared to the TDS simulation method. Where this method proved the ability to save time by approximately 1/2 of the performance time compared to the TDS method.

ACKNOWLEDGEMENTS

The authors would like to thank the University of Mosul, College of Engineering, Electrical Department, for the support given during this work and for the Ministry of Electricity (Iraq) for information support.

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