A Comparative Study of Transient Stability Power System Analysis Using Energy Function Methods for High Performance of Critical Clearing Time

Inas Jabbar Mohammed
Babylon Technical Institute , Al-furat Al- Awsat Technical University
eanas_ass@yahoo.com

Abstract :

The power system transient stability studies depend on the state of sudden disturbance to which the system is subjected, such as the fault state on the system. The increasing size of modern power systems requires fast and more efficient methods of solutions. Therefore the classical approach of repeated integrations will be length and time consuming. Investigations to overcome this difficulty led to the use of direct methods. These methods use the energy balance in the system.

This review paper presents the comparative study between the various energy function methods: Extended Equal Area Criterion (EEAC) method, Potential Energy Boundary Surface (PEBS), Relative Unstable Equilibrium Point RUEP, method with the Indirect Integration method of transient stability analysis .the methods was tested on test system 4-machine-six node and seven lines. For transient energy function transient energy and critical energy of the system are calculated in order to judge the stability of the system **.** In this study it was concluded that the Energy function methods not only avoid the time consuming solutions required in the conventional method, but also provide a quantitative measure of the degree of system stability and the PEBS method is suggested, It achieves more accurate values than other two methods (EEAC, RUEP)and confirms the traditional method .

Key words : Power system , Energy function method , Transient energy.

الخلاصة

تتركز دراسة الاستقرارية العابرة في منظومات القدرة الكهربائية على حالات الاضطراب المفاجئ التي تتعرض لها المنظومة على سبيل المثال حالات العطل التي تحدث في المنظومة.تم اعتماد الطرق غير المباشرة والطرق المباشرة لحساب زمن الإزالة الحرج للمنظومات في الطرق غير المباشر) الخطوة – خطوة (تتضمن تكرار تكامل المعادلات التفاضلية للمنظومة على طول الزمن اللازم لحالة المنظومة خلال العطل وبعده ، ويعاد هذا الحل لكل زمن إزالة عطل. ان هذه الطريقة وبالرغم من دقة نتائجها تستغر ق زمن حسابي كبيروهذا لا يتناسب مع تطور المنظومة الكهربائية لذا فأن الدراسات المستمرة وجدت طرق سريعة وكفوءه لحساب الإزالة الحرج دون اللجوء الى الاعتماد على منحنيات المتغيرات المختلفة للمنظومة لتحديد زمن الازالة الحرج وهي الطرق المباشرة التي تتجاوز الصعوبات المذكورة اعلاه وان هذه الطرق تعتمد على معيار التوازن في الطاقة.

يستعرض البحث دراسة مقارنة بين مختلف طرق دالة الطاقة المتمثلة :طريقة معيار تساوي المساحات الممتدة ،طريقة حد الطاقة الكامنة السطحية ،طريقة نقطة عدم التوازن النسبية والطرق الغير مباشرة في تحليل الاستقرارية العابرة .تم اختبار الطرق على منظومة اربعة مكائن –ستة عقد –وسبعة خطوط .لدالة الطاقة العابرة لمنظومة القدرة مركبتين دالة الطاقة العابرة والطاقة الحرجة تحتسب من اجل الحكم على استقرارية المنظومة.تم الاستنتاج في هذه الدراسة ان طرق دالة الطاقة لاتجنبنا الوقت المستقطع للحل المطلوب لكن تزودنا بدرجة القياس الكمي لاستقرارية المنظومة واقترحت طريقةPEBS . لكونها تحقق الدقة المطلوبة مقارنة بالطرقتيتين (EEAC , RUEP) والطرق التقليدية الاخرى .

الكلمات المفتاحية : منظومة القدرة ، طرق دالة الطاقة ، الطاقة العابرة .

1. Introduction:

Maintaining a reliable and uninterrupted electric service is among the primary objectives of the electric utility industry. To successfully meet this goal, power system planning engineers have devoted a good deal of their time and effort to study the transient stability of power systems under a variety of probable contingencies [Hamid

Elah1983]. The transient energy function (TEF) methods are also called the Lyapunov methods or direct methods. They examined the system stability from the viewpoint of system energy rather than in the time domain by checking the time response curves of power angles of generators in the system (Hamid Elah , 1983).

One of these methods such as, (EEAC) proceeds as follows:

1- decompose the system into two groups; one (the critical cluster CC) contains the critical machines responsible for the system separation whenever an instability occurs; the other comprises the remaining machines;
2- aggreate each group into an equivalent machine
3- replase the resulting two equivalents by a one –machine –infinite –bus (OMIB) system
4- apply to this (OMIB) the equal –area criterion (Xue , 1993).

The two methods for energy function the Potential Energy Boundary Surface (PEBS) as an approximation of an actual system stability boundary. These methods have been described

Extensively in the literature (Kakimoto , 1978 ; Athay , 1979 ; Fouad , 1987). A fault-dependent method using the concept of (Relevant Unstable Equilibriums Point RUEP.) makes the direct methods more applicable in practical systems (Athay ,1979) It is believed that the RUEP method will continue to be a viable method, in terms of its accuracy and reliability, among the direct methods for transient stability analysis (Chiang , 1991) .

One of the main aims of the transient stability analysis is to compute CCT for a given fault condition. 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.

The typical Framework for the direct method transient analysis method is:

1). Constrict an energy-type Lyapunov function which reflects the stability of the power system (simply called energy function);
2). Based on the faulted and post-fault network structure and fault process, define the critical energy value (V_{cr})
3). Solve the energy function value V_c at the end of the final operation; if $V_c < V_{cr}$ the system is stable, otherwise unstable.

In this paper possible fast stability analysis method which have been suggested elsewhere for this tool are examined and assessed in one system and comparison are made in this project

2. Extended Equal Area Criterion Method EEAC

EEAC is an extension of the Equal Area Criterion for multi machine systems and it is applied to the determination of the Transient Stability Margin (TSM) of critically disturbed machines (Fang , D2005). This method has very interesting possibilities for on-line Transient Stability Assessment (TSA). A significant advantage is the algebraic expression it provides for the calculation of critical clearing times and stability margins (Xue , 1992). This method first divides the system into an equivalent two-machine aggregated system on the assumption that, first, the system is separated into two clusters, and secondly reduces the two-machine system into a One Machine Infinite-Bus (OMIB) system. Then finally the well-known Equal Area Criterion (EAC) is used for the sensitivity analysis (Dong and pota , 1993).

2.1 Basic Assumption for EEAC:-

This method introduces the following important assumptions (Xue , 1992):

1-The disturbed systems separation depends upon the angular deviation between the following two equivalent clusters: the critical machine group (cmg) and the remaining machine group (rmg). The Partial Centre Of Angles (PCOA) of the critical machine group (cmg) (δcmg) and the partial center of angles (PCOA) of the remaining machine group

(rmg) (δrmg) are defined as follows:

$$\delta_{cmg} = \frac{\sum_{i\epsilon cmg} M_i \delta_i}{M_{cmg}} \quad (1)$$

$$M_{cmg} = \sum_{i\epsilon cmg} M_i \quad (2)$$

$$\delta_{rmg} = \frac{\sum_{j\epsilon rmg} M_j \delta_j}{M_{rmg}}$$

$$M_{rmg} = \sum_{j\epsilon rmg} M_j \quad (3)$$

2- Within an aggregated cluster: the rotor angles of individual machines are supposed to be equal to the corresponding Partial Centre of Angles (PCOA).

$$\delta_i = \delta_{cmg} \qquad i \in c \quad (4)$$

$$\delta_j = \delta_{rmg} \qquad j \in rmg \quad (5)$$

With the above two assumptions, a multi-machine system can be transformed into a two-machine system running in its own Partial Centre Of Angles(PCOA): Based on the above assumptions , a multi – machine system can be transformed into equivalent tow- machine system. Then the two – machine equivalent is reduced to a single machine infinite bus system. The equivalent One-Machine-Infinite-Bus system model is given by the following equations:

$$M\ddot{\delta} = P_{mech} - [P_c + P_{max}\sin(\delta - \gamma)] \quad (6)$$

Where

$$\delta = \delta_{rmg} - \delta_{cmg} \quad , M_T = \sum_{i=1}^{n} M_i \quad , M = \frac{M_{cmg} M_{rmg}}{M_T}$$

$$P_{mech} = M_T^{-1}\left(M_{rmg} \sum_{i\epsilon cmg} P_{mechi} - M_{cmg} \sum_{j\epsilon rmg} P_{mechj} \right)$$

$$P_c = M_T^{-1}\left(M_{rmg} \sum_{i,k\epsilon cmg} E_i\, E_k G_{ik} - M_{rmg} \sum_{j,l\epsilon rmg} E_j\, E_l G_{lj} \right)$$

$$P_{max} = \sqrt{C^2 + D^2} \quad , \gamma = \tan^{-1}\left(\frac{C}{D}\right)$$

$$C = M_T^{-1}\left(M_{rmg} - M_{cmg}\right) \sum_{i\epsilon cmg, j\epsilon rmg} E_i\, E_j G_{ij}$$

$$\mathbf{D} = \sum_{\mathbf{i\epsilon cmg, j\epsilon rmg}} \mathbf{E_i E_j B_{ij}}$$

2.2 Transient Stability Analysis By EEAC Method (Wang S2003 ; Xue , 1988) :-

From the well-known Equal Area Criterion applied to equation (6), figure (1) illustrates the plot of the P-δ curves provided in the pre-fault or original (o), during-fault (D) and post –fault (P) configuration. The original (steady -state) operation is characterized by the rotor angle δ_o located at the crossing of the horizontal line

P=Pm with the original Peleco curves, partially drawn.

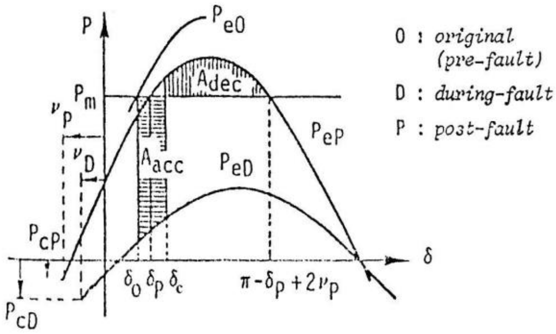

Figure (1) the Extended Equal-Area Criterion

The post-fault stable respectively unstable equilibrium point is determined by the intersection of Pm with Pep; this provides δp(respectively (π-δp+2γp). Moreover the value that the angle reaches at the fault clearing time determines the accelerating area A_{acc} and decelerating area A_{dec} which-measure the corresponding transient energies:

$$A_{acc}(P_{mch} - P_{DC})(\delta_C - \delta_o)P_{maxD}[cos(\delta_c - \gamma_D) - cos(\delta_o - \gamma_D)] \quad (8)$$

$$A_{dec} = \left(P_{cp} - P_{mch}\right)\left(\pi - \delta_c - \delta_p + 2\gamma_p\right) + P_{maxP}\left[\cos\left(\delta_c - \delta_p\right) + \csc\left(\delta_p - \gamma_p\right)\ \right] \quad (9)$$

Where:

P_{CD}, γ_D and P_{maxD} $are\ during\ fault\ parameter$; P_{cp}, γ_p and P_{maxp} $are\ post\ fault\ parameters$

δo is the pre-fault angle & equal: $\delta_O = \sin^{-1}\left(\frac{P_{mech-}P_{CO}}{P_{maxo}}\right) + \gamma_o$ (10)

δp is post-fault angle & equal: $\delta_P = \sin^{-1}\left(\frac{P_{mech-}P_{CP}}{P_{maxo}}\right) + \gamma_o$ (11)

The transient stability margin is given by $\eta = A_{dec} - A_{ac}$ (12)

For a given t and corresponding δc the critical clearing time η =0 .To calculate δc and tc for giving disturbance and its corresponding critical cluster equation (12) is used for η =0 to compute δc . δc can be solved by integration method . Using the Rung-Kutta to integrate
eq. (6) up to δ=δc, the corresponding time is the critical clearing time.

By A_{acc} and A_{dec} , we can assess the system stability as follows :

Adec <Aacc System is unstable

Adec =Aacc System is in critical state

Adec >Aacc System is stable.

3. Research Procedure:-

The integration method used for solving system differential equations is the Rung-Kutta fourth order method, and it is considered as a standard for comparison .The flow charts used for computing the Critical Clearing Time (CCT) by the EEAC, RUEP and PEBS.

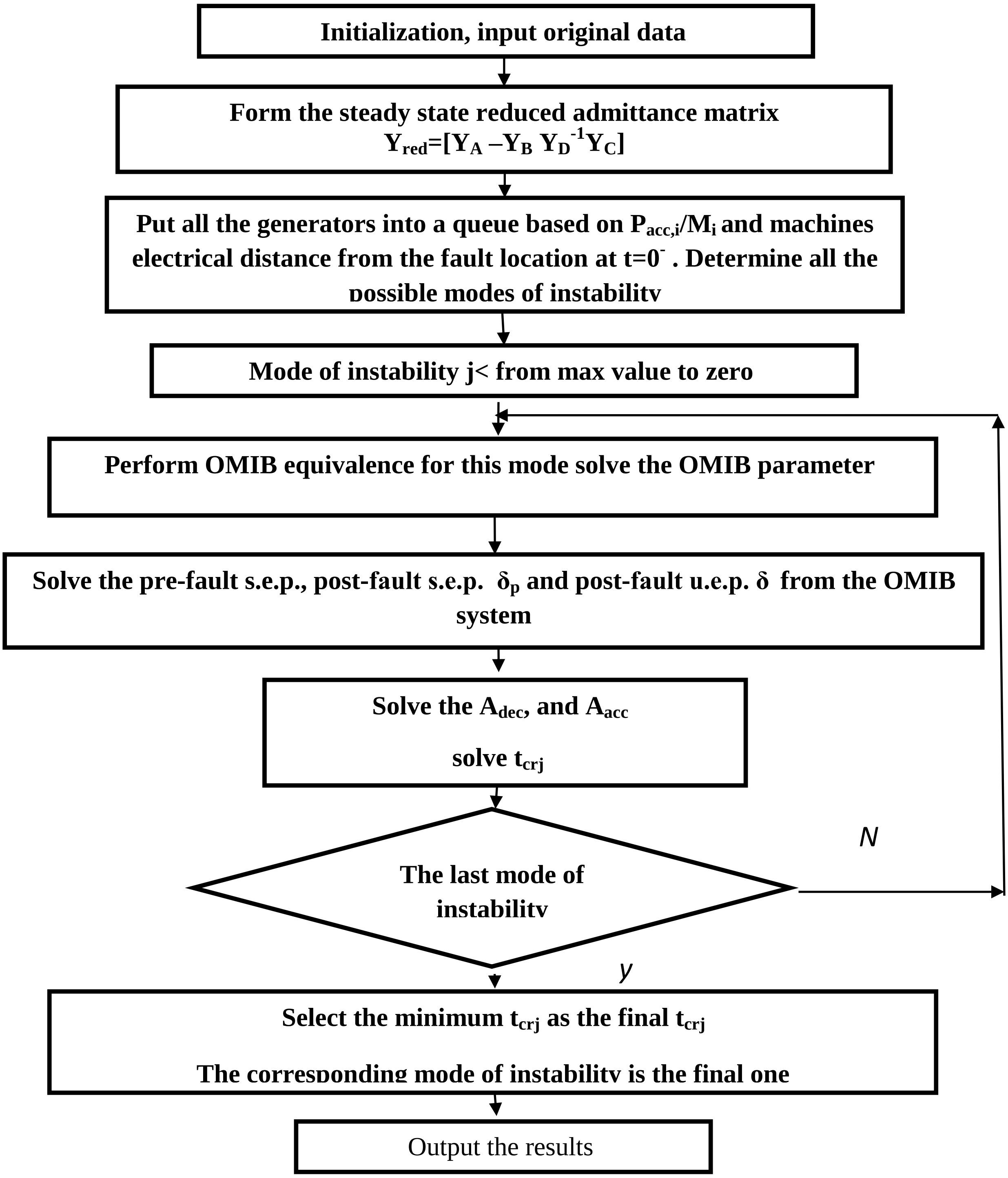

Figure 3: Flow chart of power system stability solve by EEAC method under study

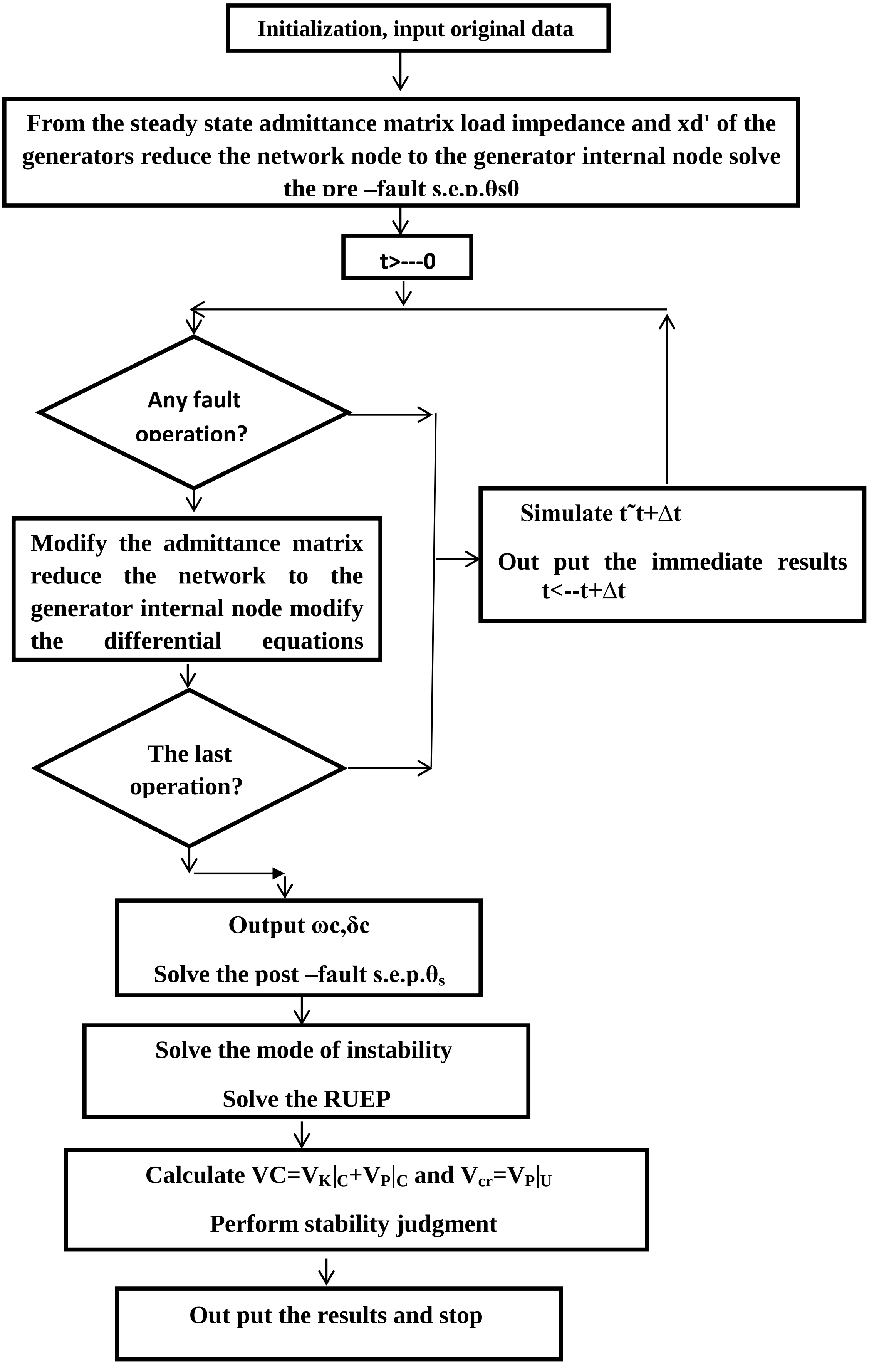

Figure 4: Flow chart of power system stability solved By RUEP method under study

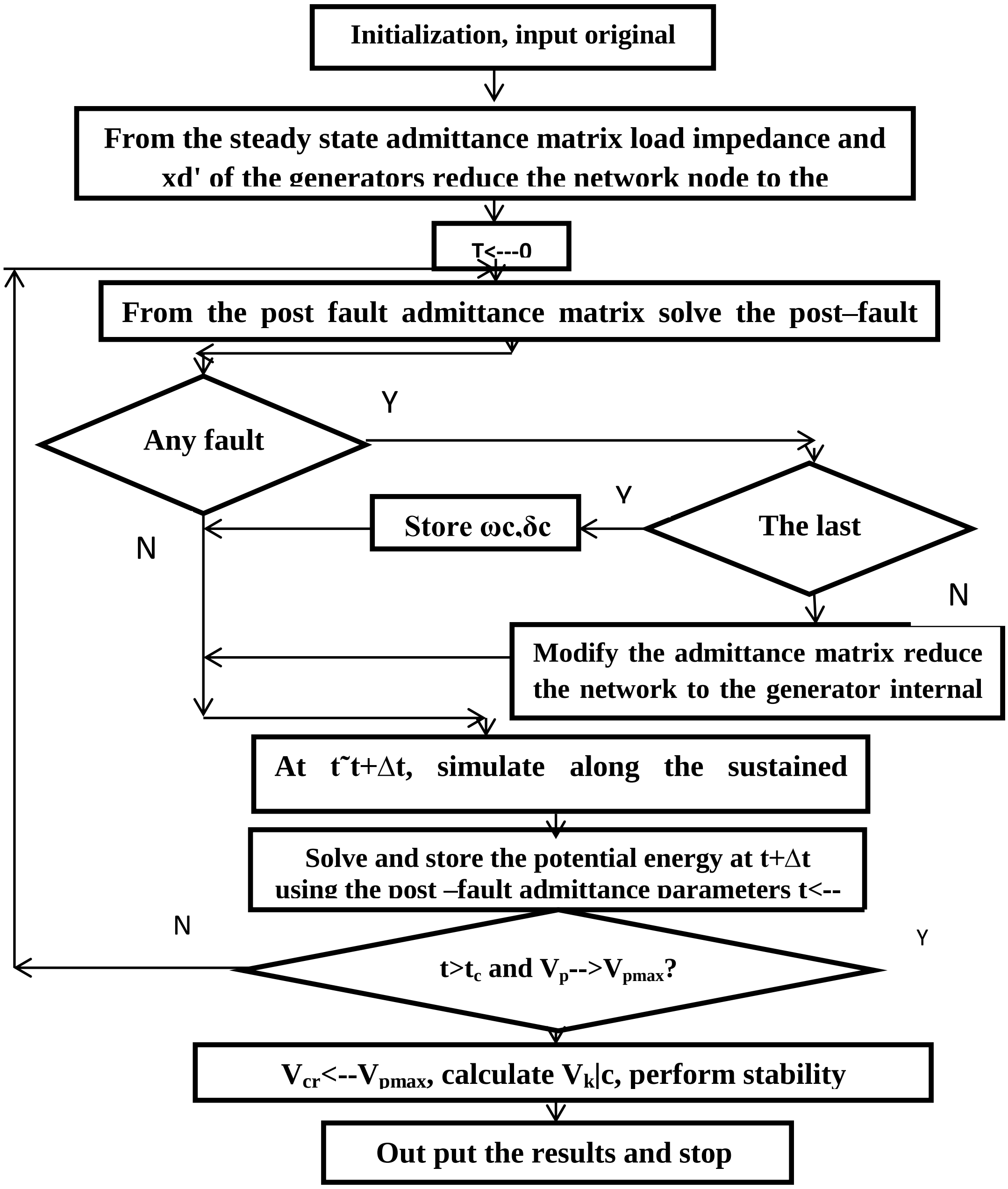

Figure 5: Flow chart of power system stability solved By PEBS method under study

5. Results Study:-

The results of assessing the transient stability of multi-machine power system using the Rung-Kutta Integration, EEAC, RUEP and PEBS method are obtained from the test system by applying the MATLAB, the results obtained are as follows**:-**

The system chosen for the study is a four-machine, six-node and seven-line system. As shown in figure 6.

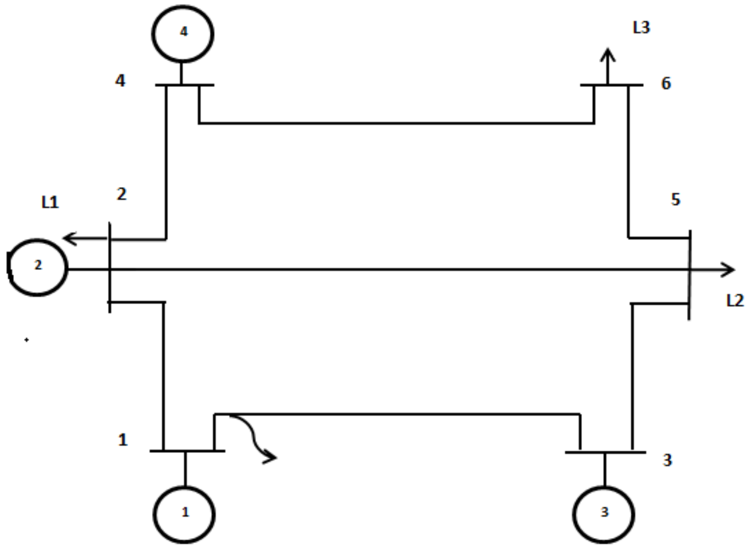

Figure 6: one line diagram for the four-machine system

Note: the impedance value given in this graph is the p.u. on the base of 100 MVA.

Considering the following two fault types:

1) 3 phases short circuit occurs on a node and the fault disappears in 0.2 s

2) 3 phases short circuit occurs on a transmission line and the faulted line is removed in 0.2 s

For the first fault type, for al1 the possible node faults in the system, the critical clearing time for each fault scenario is calculated by both the (EEAC, RUEP and PEBS) methods and the time domain simulation Step by step integration (SBS)method the results obtained by the time domain simulation method are taken to be correct. The errors of the results by the three methods are calculated. Al1 these results are given as follows:

Table1: The CCT of each scenario of the fault type 1 in the 6-node system and its corresponding error by the EEAC method.

Fault location	CCT(EEAC)	CCT(SBS)	Error (100%)
1	0.3836	0.3806	0.79
2	0.2492	0.2531	-1.54
3	0.2859	0.2906	-1.62
4	0.3586	0.3523	1.79
5	0.4734	0.4550	4.04
6	0.5172	0.5104	1.33

$$Error = \frac{t_{(EEAC,RUEP,FEBS)} - t_{SBS}}{t_{SBS}} * 100\%$$

If the resulting error is within 10%, the result is acceptable. The calculation results in Table1 indicate that for al1 the fault scenarios of this fault type, EEAC gives acceptable results. EEAC is successful in this fault type.

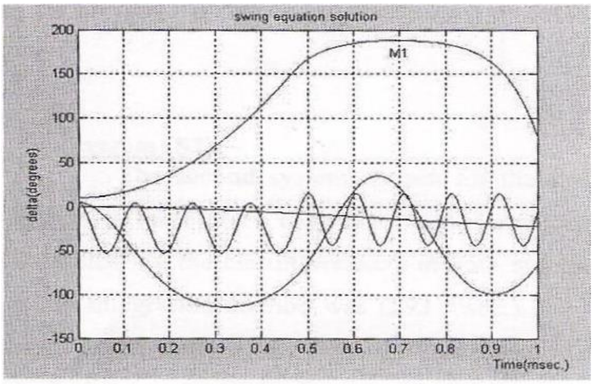

Figure7: With a temporary fault at node 1, the power angle curves of generator #2, and Generator #1 in the critical stable stat

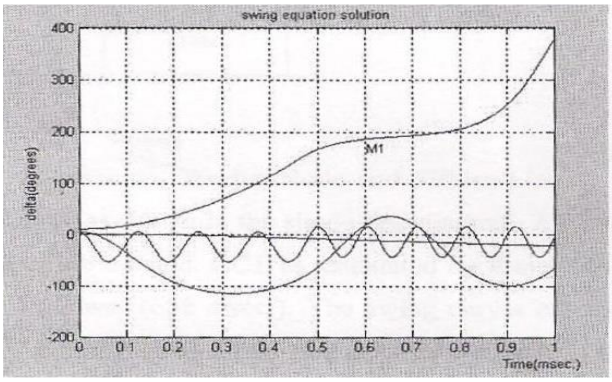

Figure 8: With a temporary fault at node 1, the power angle curves of generator #2,and Generator #1 in the critical unstable stat

Figure 7 indicates that generator #2 and generator #1 lose synchronization with a generator #4and #3in the same time. The critical machines are correctly selected, and the analysis results from the TEF method gives acceptable results in this fault scenario.

For the transient energy function transient energy and critical energy of the system are Calculated in order to judge the stability of the system. The stability margin of the system. Can be obtained from the transient energy and critical energy of the system. These values .For each fault scenario are given in table 2.

Table 2: Transient energy, critical energy, and stability margin for each scenario of the fault type 1 in the 6-node system by the EEAC method

Fault location	V_{cr}	V	T_{cl}	Margin
1	3.2625	0.5462	0.2	8.3 179
2	3.0237	1.7392	0.2	1.3330
3	3.5839	1.3969	0.2	3.9176
4	3.2625	0. 6670	0.2	6.4683
5	3.2625	0.3966	0.2	10.81
6	3.2625	0.3961	0.2	12.8065

V_{cr}: Critical transient energy of the system.
V: Transient energy of the system at fault clearing time.
T_{cl}: Fault clearing time, al1 the faults are cleared in 0.2 seconds as assumed before;
TSM: Normalized Transient Stability Margin, calculated by:

$$TSM = \frac{V_{cr-V}}{V_{keq}} \quad (13)$$

Where V_{keg} is the kinetic energy at the moment the fault is removed.

The results in the Table 2 indicate that the stability index is over 100%. That means the system is safe enough in the cases of the fault type 1. The operator may even consider increasing the load to run the system in a more economic mode if the fault type 1 is the most serious possible fault case.

Table 3: The CCT of each scenario of the fault type 1 in the 6-node system and its Corresponding error by the RUEP method

Fault location	CCT(RUEP)	CCT(SBS)	Error (100%)
1	0.3812	0.3806	0.16
2	0.2542	0.2531	0.43
3	0.2952	0.2906	1.58
4	0.3564	0.3523	1.16
5	0.4564	0.4550	-0.35
6	0.4991	0.5104	-2.21

Table 4: Transient energy, critical energy, and stability margin for each scenario of the fault type 1 in the 6-node system by the RUEP method.

Fault location	V_{cr}	V	T_{cl}	Margin
1	3.1970	0.5353	0.2	8.0936
2	2.9357	1.5774	0.2	1.4560
3	3.4595	1.1805	0.2	4.0784
4	3.1970	0. 6527	0.2	6.2993
5	3.1970	0.4780	0.2	9.5799
6	3.1970	0.3964	0.2	12.6189

Table 5: The CCT of each scenario of the fault type 1 in the 6 node system and its Corresponding error by the PEBS method.

Fault location	CCT(PEBS)	CCT(SBS)	Error (100%)
1	0.3836	0.3806	0.63
2	0.2521	0.2531	-0.40
3	0.2885	0.2906	-0.72
4	0.3583	0.3523	1.70
5	0.4513	0.4550	0.81
6	0.5963	0.5104	-0.80

Table 6: Transient energy, critical energy, and stability margin for each scenario of the fault type 1 in the 6-node system by the (PEBS) method.

Fault location	V_{cr}	V	T_{cl}	Margin
1	3.2619	0.5941	0.2	8.2381
2	2.8834	1.6006	0.2	1.2787
3	3.4651	1.3303	0.2	3.1336
4	3.2667	0.6656	0.2	6.4442
5	3.1506	0.4793	0.2	9.2853
6	3.3091	0.4223	0.2	12.5645

Table 7: The CCT of each scenario of the fault type 2 in the 6-node system and its corresponding error by the EEAC method.

Fault location	CCT(EEAC)	CCT(SBS)	Error (100%)
1 - 2	0.3461	0.3523	-1.76
2 - 4	0.3430	0.3483	-0.23
4 - 6	0.3773	0.3550	6.26
5 - 6	0.4391	0.4306	1.97
5 - 3	0.2047	0.2018	1.43
3 - 1	0.3672	0.3333	10.17

Table 8:Transient energy, critical energy, and stability margin for each scenario of the fault type 2 in the 6-node system by the EEAC method

Fault location	V_{cr}	V	T_{cl}	Margin
1 - 2	2.5504	0.6345	0.2	4.7747
2 - 4	2.5119	0.6296	0.2	4.6909
4 - 6	1.0547	0.2678	0.2	3.0306
5 - 6	1.3299	0. 2419	0.2	4.8817
5 - 3	1.1609	1.1051	0.2	0.0619
3 - 1	3.2412	0.8828	0.2	4.6421

Table 9: The CCT of each scenario of the fault type 2 in the 9-node system and its Corresponding by the RUEP method.

Fault location	CCT(RUEP)	CCT(SBS)	Error (100%)
1 - 2	0.3441	0.3523	-2.33
2 - 4	0.3414	0.3483	-0.70
4 - 6	0.3618	0.3550	1.92
5 - 6	0.4295	0.4306	-0.26
5 - 3	0.1925	0.2018	-4.16
3 - 1	0.3691	0.3333	10.74

Table 10:Transient energy, critical energy, and stability margin for each scenario of the fault type 2 in the 6-node system by the RUEP method.

Fault location	V_{cr}	V	T_{cl}	Margin
1 - 2	2.5193	0.6 174	0.2	4.7163
2 - 4	2.4835	0.6279	0.2	4.5877
4 - 6	0.98 1 5	0.2825	0.2	2.427 1
5 - 6	1.3296	0. 2406	0.2	4.8817
5 - 3	1.1609	1.1051	0.2	0.0619
3 - 1	3.2412	0.8828	0.2	4.9369

Table 11: The CCT of each scenario of the fault type 2 in the 9-node system and its Corresponding error by the PEBS method.

Fault location	CCT(PEBS)	CCT(SBS)	Error (100%)
1 - 2	0.3451	0.3523	-2.04
2 - 4	0.3426	0.3483	-0.33
4 - 6	0.3570	0.3550	0.56
5 - 6	0.3586	0.4306	0.74
5 - 3	0.2218	0.2018	9.91
3 - 1	0.3559	0.3333	6.78

Table 12:Transient energy, critical energy, and stability margin for each scenario of the fault type 2 in the 6-node system by the RUEP method

Fault location	V_{cr}	V	T_{cl}	Margin
1 - 2	2.5509	0.6 244	0.2	4.7726
2 - 4	2.5235	0.6403	0.2	4.6655
4 - 6	0.9625	0.2957	0.2	2.3771
5 - 6	1.3500	0. 2497	0.2	4.7891
5 - 3	1.8456	1.442 1	0.2	0.3962
3 - 1	3.0705	0.8884	0.2	4.1457

6. Conclusion:-

This paper reviews three methods for measuring the transient energy function of the power system. The comparison between these methods is provided. These methods are tested on one-test systems for tow fault type and the results are discussed by the percentage error between these methods. The conclusion from this work can be summarized as follows; Al1 three methods give acceptable results in 90% of the fault cases of the sample test system. Each method fails in around 10% of the fault scenarios. The failed 10% scenarios are not the same for al1 the three methods. This indicates that each method has its unique characteristic and its own coverage. EEAC is fast, but its basic theory is difficult to accept. lts basic assumption, that system always loses synchronization in a two group separation mode, is not always true in the practical power system. Error is introduced to this theory. PEBS is little slow because it simulates pan of the fault trajectory (generally from begriming to the fault clearing time). With the availability of the synchronized phasor measurement for each generator, the fault trajectory is easy to obtain from measurement. By providing an efficient algorithm to predict the post-fault trajectory, the trajectory can be obtained by integrating the differential equation. The speed of the PEBS method will be improved. Together with its wide mode1 capacity, PEBS can rival any of its counterparts in the stability analysis. More work is needed to implement this idea. RUEP gives accurate results as long as the right RUEP is ascertained. But how to locate the correct RUEP is the Achilles heel of the method. Newton's iterative method is applied to solve the RUEP. Theoretically, once an iterative method is applied for equation solution, the correct solution is not guaranteed. An iterative method cannot always get the solution which is of interest. Theoretically, the error of RUEP method cannot be eliminated completely.

For online estimation critical clearing time under real operating condition. Based on the Real Time Digital Simulation. PEBS method is suggested. It has some of the advantages of the time domain simulation method. It has a good modeling capacity. Exciter, or governor, or other complicated models can be considered. If the speed can be improved by the synchronized phasor measurement, and an efficient flow chart is found to predict the post-fault power angle curves, this method is a good choice. Future work in these areas is suggested.

7. Reference:

Athay T., Podmore R. and Virmani S., March/April 1979 , " A Practical Method for Direct Analysis of Transient Stability", IEEE Trans. PAS, Vol. 98, No. 2, pp. 473-483.

Chang H , Liu W, Xing Z, *et.al.*, 2007," Online application of power system transient stability computation". Power System Technology,31(13):54-58

Chiang H. D., Wu F. F., *et.al.*, 1991 ,"A BCU Method for Direct Analysis of Power System Transient Stability", lEEE19 91 SM4234 PWRS.

Dong Y., Pota H.R., March 1993, "Transient Stability Margin Prediction Using Equal-Area Criterion", IEE proceedings-c, Vol. 140, No. 2.

Fang D, Qin Y. , 2005 , "A new trajectory sensitivities approach for CCT assessment", Proceedings of the CSEE, 25(14):7-11.

Fouad A.A., Feb.1987 , "Direct Transient Stability Analysis Using Energy Functions, Application to Large Power Networks", IEEE Trans. on Power Systems, Vol. PWRS-2, No. 1, pp.3 7-44.

Hamid Elahi , 1983 , "Transient stability of power systems with non-linear load models using individual machine energy functions' 'Iowa State University.

Kakimoto N. , Ohsawa Y., and Hayashi M. , MaylJune, 1978 ," Transient Stability Analysis of Electric Power System Type Lyapunov Function", Trans. IEEE Parts 1 and II, Vol. 98, No.Y6

Wang S, Zhang B, Liu Y, 2003 , " Critical clearing time interval calculation and its application in contingency screening", Power System Technology, 27(10):72-77.

Xue Y., Cutsem T.V. and Ribbens M., Feb 1988,"Extended Equal Area Criterion Justifications, Generalizations, Applications" IEEE Transaction on power systems, Vol. 4, No.1.

Xue Y., Euxibie E., August 1992 ,"Extended Equal Area Criterion Revisited ", IEEE Transaction on power systems, Vol. 7, No. 3.

Xue Y., Rousseaux P., 2. Gao, Wehenkel L., Pavella M., Belhomme R., Euxibie E., Heilbronn B. , Sep. 1993 ,"Dynamic extended equal area criterion", Trans. IEEE Part 1. Basic fomulation. Aihens Power Tech .